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PROJECT X NUCLEAR ENERGY STATION

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1 Introduction

Project X is a high intensity continuous wave proton beam accelerator proposed to be built at FermiLab in the next decade [1]. The recent papers "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production"[2], "Accelerators for America's Future"[3], "Proceedings of the Workshop on Applications of High Intensity Proton Accelerators" [4], and "FermiLab Project-X Nuclear Energy Application: Accelerator, Spallation Target and Transmutation Technology Demonstration" [5] have endorsed the idea that the next generation particle accelerators would enable technological breakthrough needed for nuclear energy applications. This paper suggests how one beam line at this facility could be developed into an Energy Station for nuclear energy related research and development. The continuous wave (CW) proton beam from this accelerator will be a unique facility in the world and due to the CW nature of the beam it would provide a reactor-like irradiation environment that can provide an unprecedented experimental and demonstration facility for nuclear energy R&D that can fill an important gap in the irradiation testing needs of the US and the world. Such a facility would provide a unique opportunity for cooperation by sharing resources and capital infrastructure between the DOE Office of Nuclear Energy and the DOE Office of Science.

A versatile Project X energy station could support much needed testing of materials for DOE Office of Nuclear Energy programs to:

- Ensure the sustainability and safety of the current fleet of reactors for current lifetime extensions from 40 to 60 years, as well as future extensions from 60 to 80 years or more,
- Develop new higher performance and safer reactor fuels and materials,
- Enable the development of innovative economical small reactors,
- Enable the development of new advanced reactor concepts, such as those using liquid metal or molten salt coolants,
- Enable the development of transmutation fuels for reducing legacy wastes requiring deep geologic storage, and
- Enable the investigation of accelerator driven systems as a means for transmutation of waste from power reactors.

In addition, the Project X energy station could support DOE Office of Science programs such as the

- Fusion Program
- Isotope Production Program
- Basic science research such as ultra cold neutrons, exotic isotopes, etc.

The basic concept that is proposed for the Project X energy station is one beam line of about 1 MW power directed either horizontally or vertically to a liquid lead or lead-bismuth spallation target. The spallation target produces copious neutrons with an energy spectrum similar to a liquid metal cooled fast reactor. Neutrons produced in the spallation region escape into the surrounding target region, which is also cooled by liquid lead or lead-bismuth, and contains several test regions that contain cooling loops and neutron spectra representative of various reactor concepts. The neutron spectrum in these different regions of the facility could be tailored to produce different spectra by using moderating or filtering assemblies. Preliminary investigations indicate that fairly large volumes (~300 liters of high neutron flux (>10^{14} n/cm^2/sec) can be created that rival or surpass the limited test volumes available in existing high power test reactors. Multiple test assemblies are envisioned in this target region, surrounding the spallation target, each with an independent test region and coolant loop. Each test assembly could be designed to be removed and reinstalled independently of the others. These reconstitutable assemblies can provide tremendous flexibility in designing tests that meet client needs that will evolve over time. Extensive instrumentation and temperature control are also key attributes that can be used to provide a testing environment tailored to particular program needs. One advantage of an accelerator based system over a reactor is the proximity of the experiment instrumentation. This makes gas handling and other aspects of instrumented tests a lot easier to design and operate. This also allows some capabilities (e.g. direct pressure measurement) that can't be done when the experiment is 33 meters or more from the instrumentation. A flexible design could also potentially allow the testing of various spallation targets, such as window or windowless fluid targets like lead or lead-bismuth, or solid tungsten or tantalum targets. Such a multi-use facility could provide a test bed for developing the technologies for accelerator driven subcritical systems (ADS).

2 DOE Programs Benefitting from Energy Station

2.1 DOE Office of Nuclear Energy

The DOE Office of Nuclear Energy Research and Development Roadmap, April 2010 [6] listed four main research and development objectives:

1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors,
2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals,
3. Develop sustainable nuclear fuel cycles,
4. Understanding and minimization of risks of nuclear proliferation and terrorism.

In order to meet each of these four objectives, the DOE roadmap focuses on:

1. Aging phenomenon and degradation of system structures and components such as reactor core internals and reactor pressure vessels, as well as fuel reliability and safety performance issues,

develop and test advanced monitoring and NDE technologies, improve materials data such as composite cladding;

2. Fundamental nuclear phenomena and development of advanced fuels and materials to improve the economic and safety of advanced reactors such as corrosion resistant materials, radiation resistant alloys for fast spectrum concepts;

3. Development of a suite of sustainable fuel cycle options that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk, down-selecting fuels for once-through fuel cycles, modified open fuel cycles, and closed fuel cycles;

4. Development of the tools and approaches for understanding, limiting, and managing proliferation risks, such as options that enable decreasing the attractiveness and accessibility of used fuel and intermediate materials, and transmuting materials of potential concern.

Execution of this DOE Nuclear Energy roadmap will require access to a variety of irradiation testing environments that could potentially be addressed by the Project X Energy Station:

- Variety of neutron spectra from fast to thermal
- Variety of coolants such as water, sodium, lead-bismuth,
- Variety of fuels such as oxides, metals, molten salts,
- Variety of structural materials such as zirconium alloys, composite materials, steels

The DOE Office of Nuclear Energy organization is shown in Figure 2.1. The main programs that have R&D needs that could benefit from the Energy Station are the Office of Fuel Cycle Research and Development under Fuel Cycle Technologies and the Offices of Light Water Technologies, Office of Advanced Reactor Concepts, and Office of Gas Cooled Reactor Technologies under the Nuclear Reactor Technologies Program.

Table 2.1 summarizes the R&D priorities, environments, and testing needs of each program. Each of these programs is discussed below.

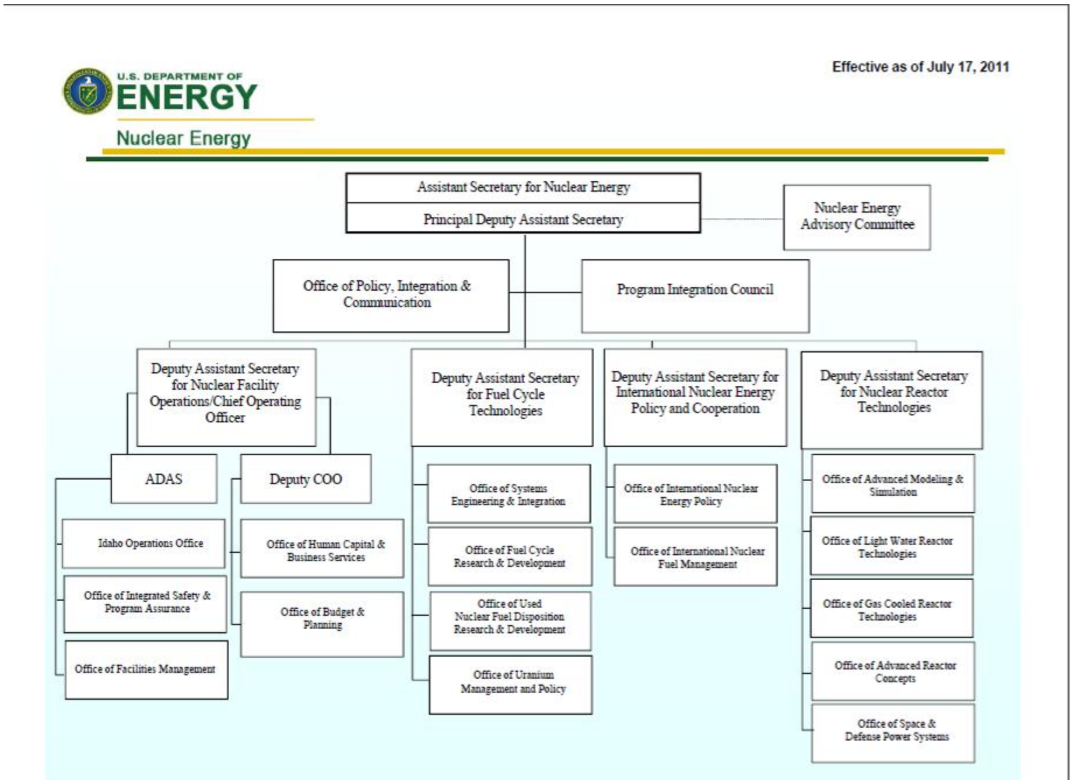


Figure 2.1. DOE Office of Nuclear Energy Programs

Table2. 1. DOE NE Program Needs

Program	R&D scope	Environment	Testing Needs
LWR Technologies	• Sustainability of current fleet of reactors • Aging and reparability • Material damage such as pressure vessel embrittlement • Reparability such as knowing when helium accumulation prevents weld repairs to structures • Safety, performance during potential accident conditions • Monitoring	Thermal Spectrum Light water moderator and coolant Zr cladding Temperature range ~300 C	Structural material properties as a function of dpa and temperature Cumulative 50-100 dpa [7,8,9]
Advanced Reactor Concepts (ARC), includes Gen-IV	• Basic physics • Material research and testing • State-of-the-art computer modeling and simulation of reactor systems and components • Probabilistic risk analysis of innovative safety designs and features • Development activities to establish concept feasibility for future deployment	**Very High Temperature Reactor (VHTR)** Thermal spectrum Graphite moderated TRISO fuel Helium cooled Temperature range ~1000 C **Supercritical water cooled reactor (SCWR)** Thermal spectrum Light water moderator and coolant Steel cladding Temperature range ~550 C **Molten Salt Reactor (MSR)** Thermal spectrum Sodium fluoride salt coolant Fuel dissolved in coolant Temperature range ~700-800 C **Gas cooled fast reactors (GFR)** Fast spectrum Temperature range ~600-850 C	Structural material properties as a function of dpa and temperature Material compatibility at operating conditions Integral tests of fuel, structural materials Feature tests of components Fuel performance with minor actinides Cumulative ~200 dpa

		Helium coolant Steel cladding **Sodium cooled fast reactor (SFR)** Sodium coolant Steel cladding Temperature range ~550 C **Lead cooled fast reactor (LFR)** Fast spectrum Pb or PbBi eutectic coolant Steel cladding Temperature range 500-800 C	
Fuel Cycle Research and Development (FCRD)	Long term science based R&D for fuel cycle technologies Develop technologies to improve sustainability of current reactors Minimize proliferation risks Develop sustainable nuclear fuel cycles • Once through • Modified open • Full recycling (transmutation) Develop improvements in affordability of new reactors • Structural materials • Nuclear fuels • Reactor systems • Instrumentation and controls • Power conversion systems • Process heat transport systems • Dry heat rejection • Separations processes • Waste forms • Risk assessment methods • Computational modeling and simulation • Small scale tests to provide proof or validation of system elements	Same as LWR and ARC above	Same as LWR and ARC above

Small Modular Reactors (SMR) *New DOE program	• Basic physics • Material research and testing • State-of-the-art computer modeling and simulation of reactor systems and components • Probabilistic risk analysis of innovative safety designs and features • Development activities to establish concept feasibility for future deployment	**Examples:** • **GEH PRISM** sodium fast reactor with metal fuel • **Toshiba 4S** small safe sodium fast reactor with metal fuel • **B&W mPower** modular PWR • **NuScale** modular PWR • **Westinghouse Small Modular Reactor –** integral PWR • **Hyperion Power Module** – lead-bismuth cooled fast reactor • **TerraPower Traveling Wave Reactor** – sodium cooled fast reactor with ~50 year fuel life • **General Atomics Energy Multiplier Module EM2** small gas cooled fast reactor	Same as LWR and ARC above Long fuel life concepts Cumulative ~300-500 dpa

2.1.1 LWR Technologies

The LWR Technologies program is focused on the sustainability of current fleet of reactors in terms of aging and reparability, such as knowing when helium accumulation prevents weld repairs to structures and material damage such as pressure vessel embrittlement. These aging issues also relate to maintaining plant safety. Table 2.2 lists some data gaps and priorities for LWR technologies.

Characteristics of a LWR environment include a thermalized neutron spectrum, light water moderator and coolant, Zr cladding, and a temperature range of around 300 °C. The maximum dose for core internal materials is 50-100 dpa and maximum helium concentration is 0.1 appm. The maximum neutron energy is ~1-2 MeV.

Table 2.2. Data gaps in the current understanding of irradiation effects on LWR core internal materials [9].

Item	Description	Priority
1	Applicability of fast reactor data to LWRs a. Material microstructure and microchemistry b. Irradiation hardening and tensile properties c. Fracture toughness database for irradiated LWR core internal materials d. Void swelling e. Irradiation creep relaxation	 M M H L L
2	Microstructure and microchemistry characterization of PWR-irradiated material	M
3	Effect of Si segregation on IASCC susceptibility	L
4	Validity of proposed K/size criterion H	H
5	IASCC crack growth rate disposition curve for PWR core internals	H
6	Fatigue crack growth rates	M
7	IASCC initiation	H
8	Effect of irradiation temperature on fracture toughness	H
9	Lower bound fracture toughness of irradiated austenitic stainless steels	M
10	Embrittlement due to void swelling	L

Priority: H high, M medium, and L low

The Project X Energy Station could support LWR Technologies by providing a thermal spectrum test environment at the relevant temperatures. A water loop with an independent cooling system could provide this environment. Metal hydrides such as zirconium hydride or calcium hydride have been demonstrated effective in providing a localized moderated neutron spectrum region in a sodium fast reactor environment, so they could also be used for spectral tailoring. The higher proportion of high energy neutrons would provide higher H and He generation rates for the same corresponding dpa accumulation, which could allow accelerated aging testing of materials. Test volumes ranging from 1 liter to 100s of liters might be possible in the LWR Energy Station test region, depending on the flux level.

2.1.2 Advanced Reactor Concepts (ARC), includes Gen-IV

The Advanced Reactor Concepts program includes the six Gen-IV systems that are being investigated. These include three thermal spectrum systems and three fast spectrum systems:

Very High Temperature Reactor (VHTR)

- Thermal neutron spectrum, graphite moderated, TRISO fuel, Helium cooled, temperature range of ~1000 °C

Supercritical water cooled reactor (SCWR)

- Thermal or potentially fast neutron spectrum, light water coolant, steel cladding, temperature range of ~550 °C

Molten Salt Reactor (MSR)

- Thermal spectrum, sodium fluoride salt coolant, fuel dissolved in coolant, temperature range ~700-800 °C

Gas cooled fast reactors (GFR)

- Fast unmoderated neutron spectrum, temperature range of ~600-850 °C, Helium coolant, steel cladding

Sodium cooled fast reactor (SFR)

- Sodium coolant, steel cladding, temperature range ~550 °C

Lead cooled fast reactor (LFR)

- Fast or unmoderated neutron spectrum, Pb or PbBi eutectic coolant, steel cladding, temperature range of 500-800 °C

The maximum dpa range for core internal structures are in the range of 30 to 200 dpa. The maximum helium concentration in structural materials is 3-40 appm. The maximum neutron energy is ~1-3 MeV.

Next-generation reactors, whether based on any of these technologies, require materials that are much more radiation resistant than those used in today's reactors. Next generation reactor materials will also have to survive in the high temperature, potentially reactive environments. Accelerators can spur the development of these next-generation materials by producing radiation environments similar to those found in future reactors, providing a platform for materials development that does not currently exist.

The Project X Energy Station could support ARC Technologies by providing both thermal spectrum and fast spectrum test environments at the relevant temperatures. A key advantage of the versatile Energy Station concept is that there is room for separate sodium, lead, helium, molten salt, and water loops with independent cooling systems that could provide the environments needed to simultaneously test materials *for each concept. Metal hydrides such as zirconium hydride or calcium hydride have been demonstrated effective in providing spectral tailoring in a sodium fast reactor environment, so they could also be used for spectral tailoring as needed for each concept. The higher proportion of high energy neutrons would provide higher H and He generation rates for the same corresponding dpa accumulation, which could allow accelerated aging testing of materials.*

2.1.3 Fuel Cycle Research and Development (FCRD)

The FCRD program conducts long term science based R&D for fuel cycle technologies. This includes 1) developing technologies to improve the sustainability of current reactors, 2) developing improvements in affordability of new small modular reactors and high temperature reactors through improved structural materials and fuels, 3) Developing sustainable nuclear fuel cycles, and 4) minimizing proliferation risks.

Fuel Cycle Research and Development Areas include structural materials, nuclear fuels, reactor systems, instrumentation and controls, power conversion systems, process heat transport systems, dry heat rejection, separations processes, waste forms, risk assessment methods, computational modeling and simulation, and small scale tests to provide proof or validation of system elements. Three variations of fuel cycles are being investigated, Once-through, Modified open, and Full recycling (transmutation).

The FCRD program is developing transmutation fuel technologies to reduce the quantity of high level nuclear waste for deep geologic disposal. Plutonium and minor actinides such as neptunium and americium are included in the fuel matrix where they are burned along with the other fuel isotopes in fast spectrum reactors.

These transmutation fuels cannot be qualified for use until candidate fuels have been irradiated and tested in a prototypic environment. Gaining access to fast spectrum irradiation testing facilities is very difficult, since there are only a few facilities in Asia that can do this type of testing.

A key challenge facing the nuclear fuel cycle is reducing the radiotoxicity and lifetime of spent nuclear fuel. Partitioning or sorting of nuclear waste isotopes and accelerator-based transmutation combined with geological disposal can lead to an acceptable societal solution to the problem of managing spent nuclear fuel. Accelerators can also drive next-generation reactors that burn non-fissile fuel, such as thorium, that can be burned with the use of particle beams. Both or either of these approaches could lead to an increase in power generation through greenhouse gas emission-free nuclear energy and could provide a long-term strategy for the growth of nuclear power in the U.S.

For spallation accelerator driven systems, there is a variety of potential concepts, characterized by both thermal and fast neutron energy spectra. The leading candidates are proton accelerators with liquid lead or lead-bismuth eutectic spallation targets, surrounded by a multiplying blanket which is essentially a subcritical reactor driven by the accelerator spallation neutron source. The temperature range of materials is similar to water cooled or liquid metal cooled fast reactors, which is 140-600 C. The maximum dose for structural materials is in the range of 50 to 100 dpa. Maximum helium and hydrogen concentrations are ~5000 appm/fpy and 50,000-100,000 appm/fpy, respectively. The maximum neutron energy extends to several hundred MeV.

The Project X Energy Station could support FCRD Technologies by providing both thermal spectrum and fast spectrum test environments at the relevant temperatures. A key advantage of the versatile Energy Station concept is that there is room for separate sodium, lead, helium, molten salt, and water loops with independent cooling systems that could provide the environments needed to simultaneously test materials for each concept. Metal hydrides such as zirconium hydride or calcium hydride have been demonstrated effective in providing spectral tailoring in a sodium fast reactor environment, so they could also be used for spectral tailoring as needed for each concept. The higher proportion of high energy neutrons would provide higher H and He generation rates for the same corresponding dpa accumulation, which could allow accelerated aging testing of materials. Candidate fuel and cladding materials can be irradiated in a prototypic environment of coolant, neutron spectrum, and temperature. The temperature is a critical parameter in materials irradiation, and precise temperature control will be a key aspect of the Energy Station design. The peak neutron flux in the test regions is about half that achieved in existing fast test reactors.

2.1.4 Small Modular Reactors (SMR) Program

Although still under development, the objective of the DOE NE Small Modular Reactor Program will be DOE support or partnerships with industry development and licensing. Industry is taking the lead in developing concepts, and DOE will provide the R&D to support maturation of the designs to allow licensing. Examples of SMR concepts being proposed by industry include:

- GEH PRISM sodium fast reactor with metal fuel
- Toshiba 4S small safe sodium fast reactor
- B&W mPower modular PWR
- NuScale modular PWR
- Westinghouse Small Modular Reactor
- Hyperion Power Module – lead-bismuth cooled fast reactor
- TerraPower Traveling Wave Reactor – sodium cooled fast reactor with ~50 year fuel life
- General Atomics Energy Multiplier Module EM2 small gas cooled fast reactor

Research and Development is oriented to basic physics, material research and testing, state-of-the-art computer modeling and simulation of reactor systems and components, probabilistic risk analysis of innovative safety designs and features, and development activities to establish concept feasibility for future deployment.

The Project X Energy Station could support SMR Technologies by providing both thermal spectrum and fast spectrum test environments at the relevant temperatures and coolants. A key advantage of the versatile Energy Station concept is that there is room for separate sodium, lead, helium, molten salt, and water loops with independent cooling systems that could provide the environments needed to *simultaneously test materials for each concept. Metal hydrides such as zirconium hydride or calcium hydride have been demonstrated effective in providing spectral tailoring in a sodium fast reactor environment, so they could also be used for spectral tailoring as needed for each concept. The higher proportion of high energy neutrons would provide higher H and He generation rates for the same corresponding dpa accumulation, which could allow accelerated aging testing of materials.*

2.2 DOE Office of Science

Table 2.3 summarizes the DOE Office of Science Programs that could benefit from Energy Station, which are primarily the Fusion Program and Isotope Production Program.

Table 2.3. Environment needed for irradiation testing to support fusion and isotope production programs.

Program	R&D scope	Environment	Testing Needs
Fusion	Technology gaps requiring materials qualification • Plasma facing components • Low activation materials • safety	Tritium producing lithium blanket	Structural material properties as a function of dpa and temperature Cumulative 150-200 dpa
Isotope Production	Production methodology	Neutron spectrum tailored to specific isotopes Short half life isotopes require rabbit system	Low activation structural materials Target-structure compatibility

2.2.1 Isotope Production

There are very limited Isotope Production capabilities in the US. Two examples of isotopes in need are ^{238}Pu and beneficial isotopes.

For ^{238}Pu there is no domestic source for NASA to use as a power supply for deep space missions. DOE has the responsibility for supplying NASA's needs, and has identified some potential for production in HIFR and ATR, but has not initiated that option. In the past, this isotope was purchased from Russia, but this source is no longer available.

Beneficial Isotopes are produced in very limited amounts from ATR, HFIR, University reactors, and cyclotrons. There is no capacity to ramp up production to meet growing needs for a variety of diagnostic, therapeutic, and industrial isotopes.

The Project X Energy Station could support Isotope Production by providing irradiation environments spectrally tailored for isotope production at the relevant temperatures and coolant for the targets. Spectrum tailoring can be used to enhance production for specific isotopes by using a variety of moderators such as D_2O, graphite, beryllium, and metal hydrides. A rabbit system can be used for rapid insertion and removal for short half life radioisotope. Rather than just allow neutrons to leak out of the *various test regions to be captured in shield materials, the option of beneficial use of these leakage neutrons for isotope production, such as ^{238}Pu or ^{60}Co could be considered.*

2.2.2 Fusion

The DOE fusion program is part of an international effort developing magnetically confined nuclear fusion reactors such as the International Thermonuclear Experimental Reactor, or ITER, under development in France by an international consortium, and subsequent demonstration and commercial power plants. Materials must be developed that can survive the fusion environment. Low activation materials are required to allow maintenance. There is a parallel program developing inertial fusion concepts. Materials surrounding the fusion ignition region must also survive in a demanding environment.

Technology gaps for fusion reactor research and development requiring materials qualification include:

- Plasma facing components
- Low activation materials
- Solid breeder materials
- safety

Both low activation structural materials and tritium-producing blanket materials are being developed for fusion applications. Structural material properties are needed as a function of dpa and temperature with a cumulative ~150-200 dpa and a temperature range of 550-1000 C. Prototypic neutron energies are predominantly at 14 MeV. Maximum helium and hydrogen concentrations are ~1500 appm and ~6750 appm.

First wall and structural materials in a future fusion power plant will be exposed to a 14 MeV neutron flux which cannot be created in a test reactor. The design, licensing, and safe operation of a fusion reactor will require materials to be qualified in a neutron source that simulates fusion-relevant neutron spectra and temperatures. An accelerator is the only way to generate a neutron flux environment that approaches fusion reactor first-wall conditions.

A neutron source for the qualification of fusion reactor materials should meet the following criteria:

- Neutron spectrum with neutrons up to the energies corresponding to the first wall/blanket conditions in a future fusion reactor
- Continuous mode operation with high availability
- 20-50 dpa/fpy in high flux region allowing accelerated testing
- Irradiation volume on the order of 0.5-1 liter in the high flux region

The fusion program ITER facility plans to test at least 7 blanket types in test blanket modules

- Helium-cooled Lithium-Lead blanket
- Dual-Coolant (He and LiPb) type Lithium-
- Lead (DFLL and DCLL) blankets
- Dual-Coolant (He and LiPb) Lithium-Lead
- Ceramic Breeder (LLCB) blanket

- Helium-cooled Ceramic/Beryllium blanket
- Water-cooled Ceramic/Beryllium blanket

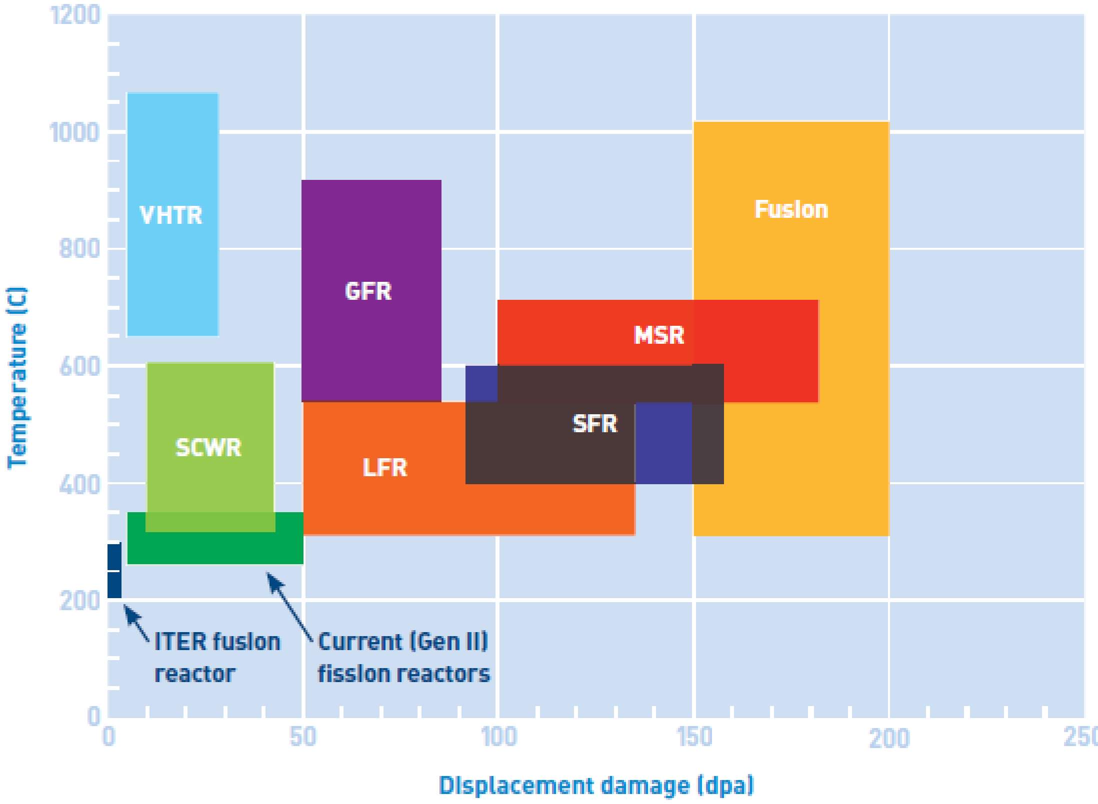
The Project X Energy Station could support fusion research and development in a dedicated fusion loop or in the materials testing station. The dpa accumulation and high energy neutron spectrum component in the Energy Station test regions can simulate the environments encountered in fusion facilities, making the Energy Station well suited for fusion reactor materials testing.

2.3 Summary of Testing Needs

Table 2.4 summarizes the testing environments for the various programs. Figure 2.2 shows the temperature ranges for the various programs. Development of materials for these future reactors will require studies of material performance to >100 dpa. The current test reactors cannot achieve those goals. The Project X Energy Station could provide that testing environment.

Table 2.4 Summary of Testing Environments [10]

Parameter	LWR	SFR	MSR	HTGR	Fusion	ADS
Temperature range	~300 °C	~550 °C	700-800 °C	600-850 °C	550-1000 °C	140-600 °C
Max DPA	50-100 dpa	100-200 dpa	100-200 dpa	5-30 dpa	~150-200 dpa	50-100 dpa
Max helium conc	~0.1 appm	~40 appm	~3 appm	~3 appm	~1500 appm	~5000 appm/fpy
Max Hydrogen conc					~6750 appm	~50,000-100,000 appm/fpy
Max Neutron Energy	<1-2 MeV	<1-3 MeV	<1-2 MeV	<1-2 MeV	<14 MeV	Hundreds of MeV
Coolant	water	sodium	Molten salt	Helium	lithium	Lead/ lead bismuth



A common theme for fusion and advanced fission is the need to develop high-temperature, radiation-resistant materials. The figure shows operating regions in material temperature and displacement damage (measured in lattice displacements per atom) for current fission reactors and future fission and fusion reactors. Fission reactors include very-high-temperature reactors (VHTR), supercritical water-cooled reactors (SCWR), gas-cooled fast reactors (GFR), lead-cooled fast reactors (LFR), sodium-cooled fast reactors (SFR), and molten-salt reactors (MSR). ***Image source: S.J. Zinkle, OECD/NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007***

Figure 2.2 Temperature ranges for testing various DOE program concepts [7]

Table 2.5 summarizes the different programs that would utilize the Project X energy station if it was available and met the program needs for irradiation testing.

Table 2.5 Summary of Programs Benefiting from Project X Energy Station

	Material (Temp Cont.)	**ADS/ LFR (lead)**	**HTGR (Helium)**	**SFR (sodium)**	**LWR (water)**	**MSR (Fl salt)**	**Fusion (Lithium)**	**Other - Nuclear Data Isotope Prod.**
Fuel Cycle R&D (NE)	X	X	X	X	X	X		X
Used Nuclear Fuel Disposition R&D (NE)		X						X
Advanced Modeling & Simulation (NE)		X	X	X	X	X		X
LWR Technologies (NE) (Industry)	X				X			
Gas Reactor Technologies (NE)	X		X					
Advanced Reactor Concepts (NE)	X	X	X	X	X	X		X
Small Modular Reactors (NE) (Industry)	X		X	X	X	X		
Space & Defense Power (NE)	X		X	X	X			X
Fusion (SC)	X						X	
Isotopes (SC)	X							X

3 Reactor Irradiation Testing Facilities are Limited Globally

Currently, the ability to progress the designs and investigations of all of the above programs by addressing key feasibility questions and filling in recognized data gaps is severely limited by the scarcity of irradiation testing facilities worldwide. Thus, there is a widely recognized need for additional irradiation testing capability in the US and worldwide, especially for evaluating fast neutron energy spectrum technologies.

New reactor materials are qualified for specific neutron flux and operating temperatures through irradiation testing of components or surveillance samples in similar environments. Irradiated materials are removed and post irradiation testing is performed. The facilities for performing this type of testing are fast reactors, thermal reactors, and spallation sources which are severely limited around the world.

Large scale (>10 MW) thermal spectrum test reactors in the US are limited to

- HFIR –thermal spectrum, water cooled, water moderated, limited volume
- ATR –thermal spectrum, water cooled, water and beryllium moderated, limited volume, limited power, non-interference with Navy primary customer

The HIFR is a small reactor and though it has a high neutron flux, the irradiation volumes available for testing are very limited and mostly occupied by existing testing and isotope production. Fuel testing is limited by the small volumes and reactivity impacts on reactor operation. These reactors produce 6-10 dpa per year.

Fast spectrum test reactors in the US no longer exist. Internationally, there are few viable options.

- BOR-60 Russia near end of life
- BN-600 not designed as test reactor
- Chinese fast test reactor just started up
- Joyo, Monju in Japan currently shutdown, fast reactor research on hold pending national evaluation of direction of energy policy
- Phenix in France recently shut down

These reactors can produce 30-40 dpa per year.

Table 3.1 High Power Test Reactors [10]

Test Reactor	country	Fast flux (>0.1MeV) $10^{14}n/cm^2/s$	Dpa/yr in steel	Useful volume (L)	Temp range (°C)	Comments
ATR A, H B I Flux traps	USA	 2.3 0.8 0.03 2.2	 6-10/yr 6-8/yr	 0.240 1.390 5.560 5560	 50-1500	Water cooled Thermal spectrum Navy program has priority Capsule diameter <127 mm Large irradiation volume Versatile facility Irradiation volume currently heavily subscribed for DOE-NE programs
HFIR Target pos 37 Radial blanket pos 8	USA	 1.1 5.3	 18/yr 5-7/yr	 0.100 0.720	 - 300-1500	Water cooled Thermal spectrum Very high peak flux Smaller volumes
Joyo	Japan	40	~30/yr	>10.	300-700	Sodium cooled Fast spectrum Temp control possible Currently shut down for repairs
BOR-60	Russia	30	~20	0.358	300-700	Sodium cooled Fast spectrum Passive instrumentation

4 Concept of Nuclear Energy Station

A common need for the design of fission and fusion reactors is the capability to develop materials and structures that can function reliably for a long time in environments with high temperatures, reactive chemicals, high stresses, and high radiation levels. Such environments can be simulated by the high intensity neutron source from a continuous wave proton linac coupled with a spallation target. The basic concept that is proposed for the Project X energy station is one beam line of about 1 MW power directed either horizontally or vertically to a liquid lead or lead-bismuth spallation target. The spallation target produces copious neutrons with an energy spectrum similar to a liquid metal cooled fast reactor. Neutrons produced in the spallation region escape into the surrounding target region, which is also cooled by liquid lead or lead-bismuth. Fairly large volumes of neutron flux can be created that rival or surpass the limited test volumes available in existing test reactors. Multiple test assemblies are envisioned in this target region, surrounding the spallation target, each with an independent test region and coolant loop. Each test assembly can be removed and reinstalled independently of the others. These reconstitutable assemblies can provide tremendous flexibility in designing tests that meet client needs that will evolve over time. Extensive instrumentation and temperature control are also key attributes that can be used to provide a testing environment tailored to particular program needs. Effects of any differences in neutron spectra between those simulated by flux tailoring in the Energy Station modules and the individual reactor concepts can be evaluated through comparable materials irradiations and interpretation of the results.

The key capabilities leading to our concept for the Energy Station include:

- Flexibility to support multiple simultaneous irradiation test regions and maximize irradiation volumes:

  - *The various energy station modules allow the ability to handle a variety of coolants in the multiple test region (He, sodium, lithium, lead, NaK, water)*

  - *The high flux test volumes will generally be ~ 1 liter for each test section. Figure 4.1 shows how miniaturized material test specimens were used to maximize a limited test volume in the high flux region for the Fusion Material Irradiation Test Facility (FMIT) design [11] (see Appendix A). A similar target region design could be applied to each module of the Project X Energy Station.*

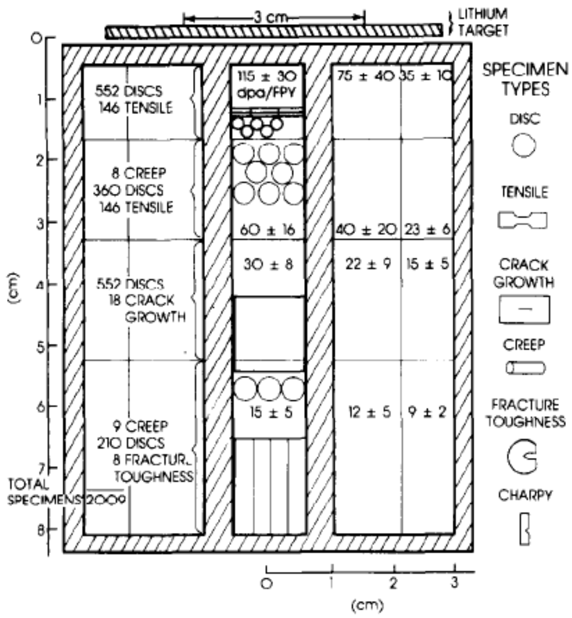
  - *Independent cooling system for each test section*

  - *Modular test sections – each can be removed and the active section shipped offsite for processing*

  - *Spallation neutrons energy distribution similar to fast reactor fission spectrum, but with a high energy tail up to the proton energy. This leads to H and He generation in materials higher than in a reactor, allowing accelerated aging testing,*

- *The neutron spectrum in each test module can be tailored from fast to thermal neutron energies by using appropriate neutron moderating materials. The gamma to neutron flux ratio can also be tailored by the choice of materials in each test module.*

- *The power generated in each test module will depend on the independent cooling system capabilities for each module. The test region power is expected to be sufficient to allow at least single fuel pins or small clusters of fuel pins to be irradiated to goal burnup in temperature and coolant environments typical of future advanced reactors.*



TEST TYPE	FLUENCES (dpa)	TEMPERATURE (NO.)**	SPECIMENS
TEM DISCS (C.M.)	5-100	4	2400
TEM DISCS (F)	5-100	3	450
TENSILE (POSTIRRADIATION)	5-100	3	240
CREEP RATE	TO 100	3	30
BEAMS (MULTIPURPOSE)	5-50	3	90
TEM DISCS (M)	2-10	4	1800
TEM DISCS (C)	2-10	4	2160
TEM DISCS (F)	2-20	3	2160
CREEP/RUPTURE	TO 50	3	225
STRESS RELAX (IN SITU)	3 PREIRRAD.	3	270
BEAMS, PREIRRAD.	2-10	3	180
TENSILE (POSTIRRAD. AND DISPENSATION)	5-50	3	1080
IN SITU CYCLIC STRESS (M)	5-50	3	180
ALT MAT'LS (M)	2-10	2	360
ALT MAT'LS (POSTIRRAD. MECH/ELEC)	2-10	2	360
IN SITU CYCLIC FLUX	5-50	3	180
TEM DISCS	0.2-5	3	680
TEM DISCS (CORRELATE TO RTNS-II)	0.2-2	3	180
TEM DISCS (SEED MICROSTRUC)	0.2-2	3	810
CREEP RATE	TO 5	3	30
TENSILE (SEED MICROSTRUC)	0.2-2	3	810
			14,575

*C-CHEMICAL ANALYSIS OF TRANSMUTATION EFFECTS
M-MICROSTRUCTURAL EVOLUTION EVALUATION
F-DEFORMATION FLOW PROPERTIES BY HARDNESS TESTS
**TEMPERATURES OVER RANGE OF 50-650°C

Figure 4.1 Example of FMIT test volume with thousands of miniature irradiation test specimens in a very small volume [11].

► Robust technology allows the Energy Station to be designed and constructed with today's technology in order to fill gaps in tomorrow's technology

- *Previous projects at Hanford that PNNL played a key role in, and has access to the detailed design documentation and extensive records, included the Fast flux Test Facility (FFTF)[10] and the Fusion Materials Irradiation Test Facility (FMIT) [11]. Both had unique capabilities that are similar to those envisioned for the Project X energy station. The FFTF is a 400 MW thermal sodium cooled fast neutron spectrum test reactor that was built and operated successfully for 10 years at Hanford. The FMIT facility was a 35 MeV, 100 mA accelerator with a 3.5 MW deuteron beam on windowless flowing lithium metal target designed expressly for fusion materials irradiation testing. A detailed design and full-scale component testing was completed in the 1980's, but the facility was not built.*

- *Reconstitutable Irradiation Test Vehicles are envisioned with independent self-contained coolant loop similar to Fusion Materials Irradiation Test (FMIT) facility design. Lessons learned from the detailed design and full scale mockup testing of the FMIT facility at Hanford in the 1980's can be applied to the design of the Project X Energy Station, since there are similar test environment conditions. Figure 4.2 shows a cutaway view of the FMIT facility design. Figure 4.3 shows how the shielding and remote manipulators were used in the FMIT design to allow test assemblies to be inserted, removed, and reconstituted with operator safety in mind.*

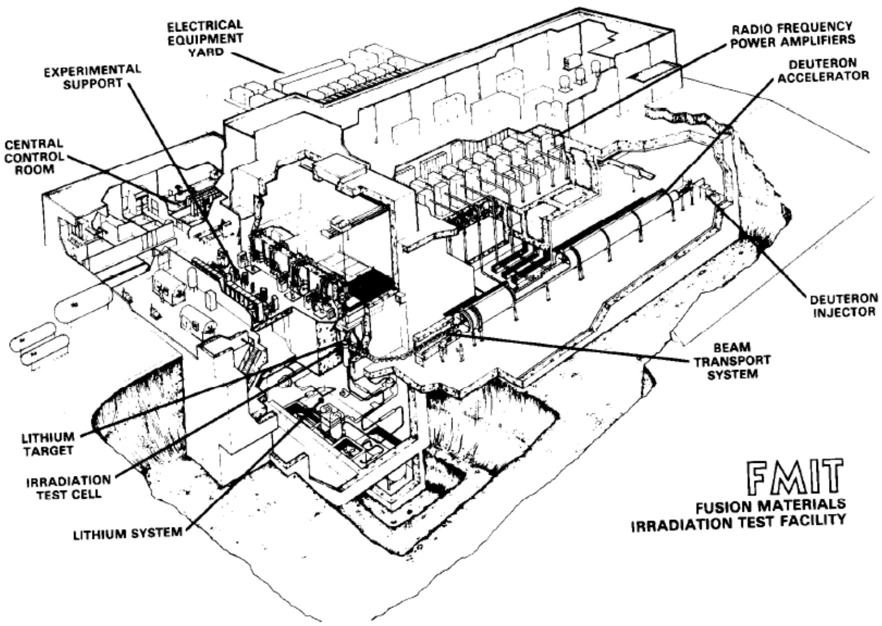


Figure 4.2 FMIT Facility Design

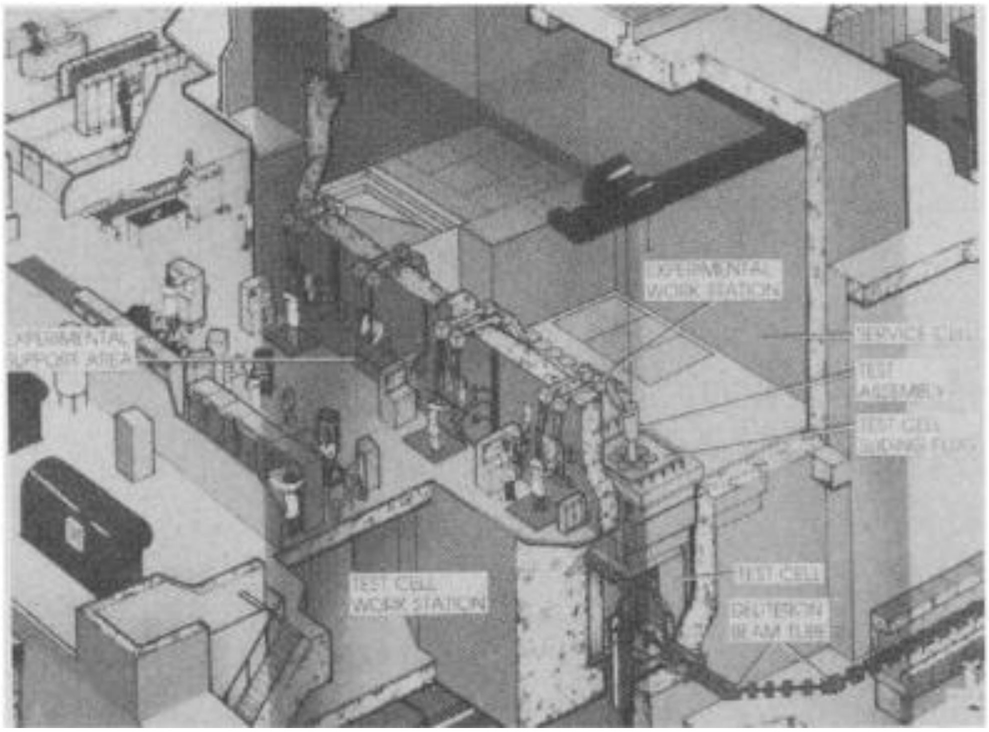


Figure 4.3 Cutaway of FMIT Workstations, remote manipulators, and test assembly access

- Spallation target surrounded by an array of test regions maximizes test volume.
    - *Figure 4.4 shows how the independently cooled, reconstitutable, vertical test assemblies were designed for the FMIT facility. In FMIT, a separate NaK cooling system was used to remove the heat deposited in the test region. Each test module could be lifted with an overhead crane for removal and insertion.*

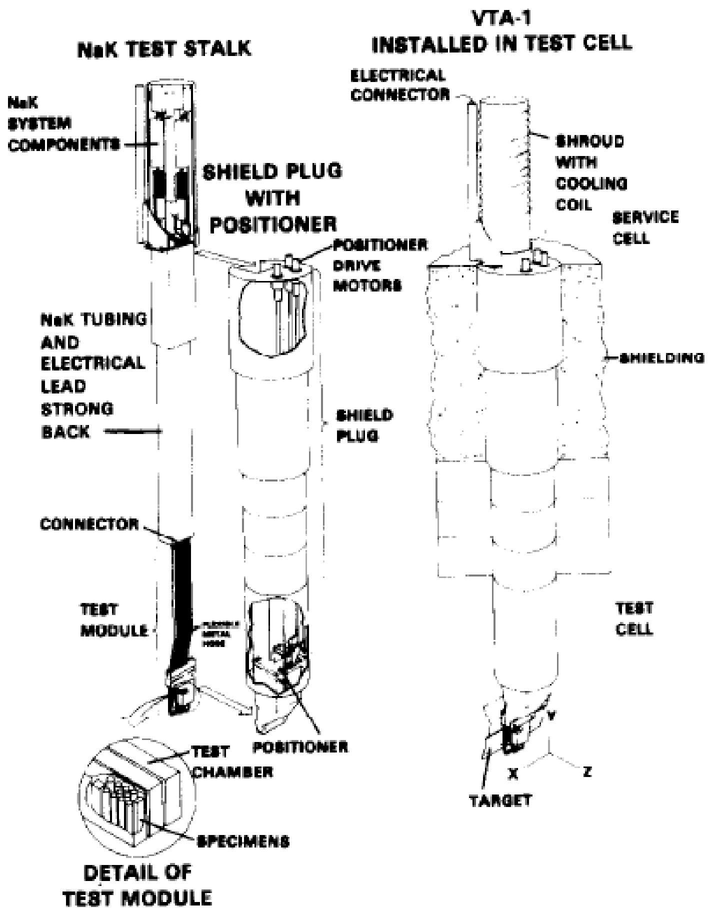


Figure 4.4 FMIT Test Module with independent cooling system

- Instrumented, temperature controlled testing capability similar to Fast Flux Test Facility (FFTF) Materials Open Test Assembly (MOTA).

    - *Figure 4.5 shows an instrumented fuel test assembly and instrumented materials test assembly irradiated at FFTF. The liquid sodium coolant, temperatures, and neutron flux environment in the FFTF provided irradiation test conditions similar to those expected for the Project X energy station. The FFTF irradiation test assembly high temperature thermocouples, online test capsule temperature control through adjustable cooling gas mixtures, and design features that allowed the monitoring, control, and reuse of the test assemblies could all be adapted to and implemented in the Project X energy station design.*

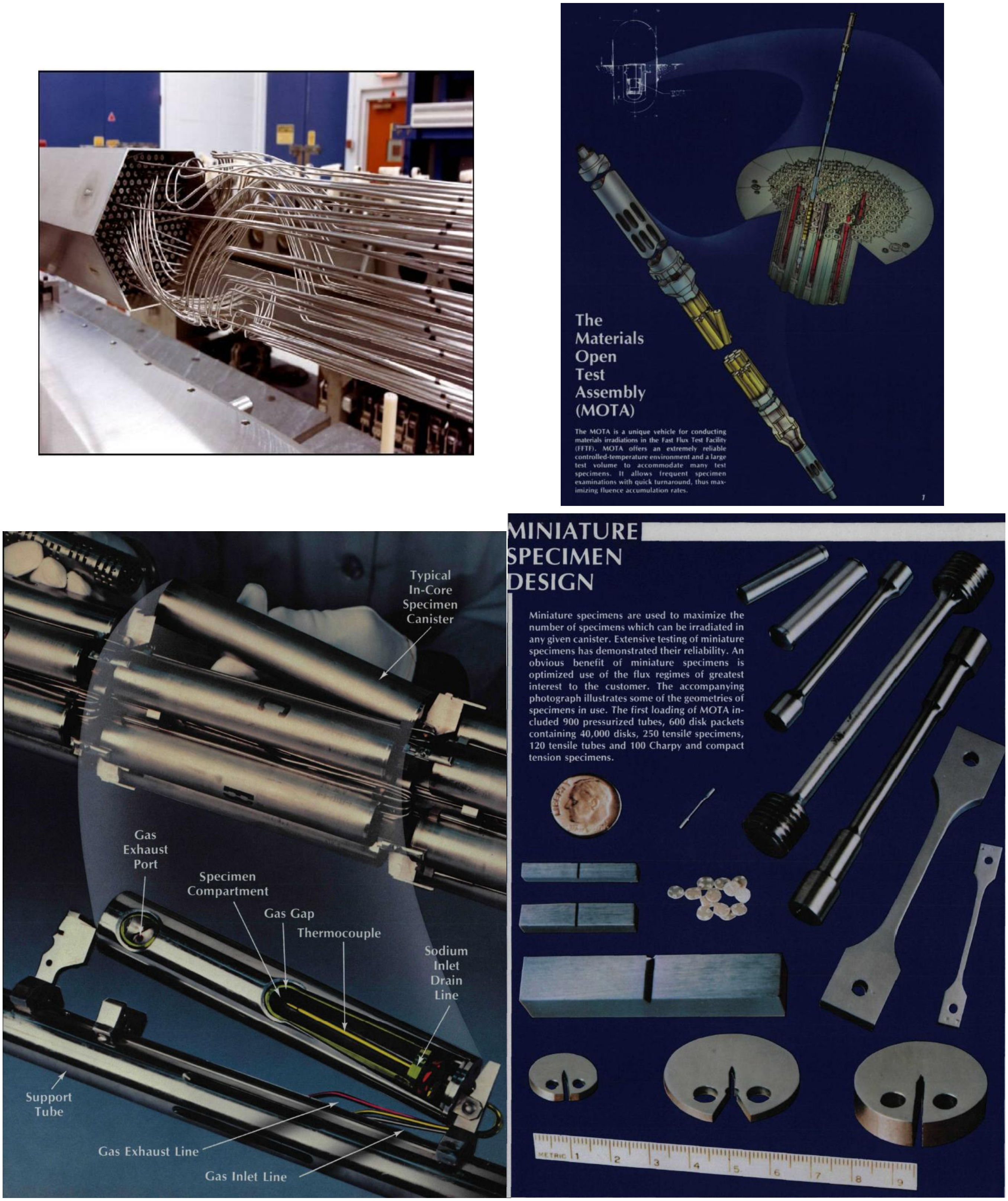


Figure 4.5. Instrumented test assemblies and material specimens at FFTF [12]

- Continuous wave, high availability, high beam current
    - *Potential for irradiation tests to high fluence to meet accelerated dpa accumulation*
- Beneficial isotope production simultaneous with irradiation testing
    - *Dedicated isotope production module with potential for rabbit system provides significant capabilities not available anywhere else.*
    - *Option of beneficial use of leakage neutrons for isotope production by surrounding test irradiation modules with moderated isotope production region, such as for ^{238}Pu or ^{60}Co.*
    - *Spallation reactions on target (lead or lead-bismuth) produce broad range of reaction products similar to fission products – some gaseous and mobile, so a cleanup system is needed. This cleanup system could also be a source of beneficial isotopes. The FFTF sodium coolant system demonstrated successful sodium cleanup systems based on cold trap technologies. These systems were effective in removing fission products and activation products from the liquid metal coolant and could be adapted to the Project X energy station conditions for continuous cleaning of the spallation target impurities generated by the spallation process.*
- Testing Infrastructure requires
    - Design capabilities
    - Fabrication capabilities
    - Shipping capabilities
    - Postirradiation examination capabilities

Figure 4.6 shows a cross sectional schematic depiction of a concept of how the Energy Station could be configured. This accelerator beam and target arrangement could be developed in either a vertical or a horizontal layout. A horizontal layout could offer benefits for the accelerator design, since it would eliminate the need for a 90 degree bend in the beam. The various energy station modules could also be arranged in a vertical or horizontal arrangement around the vertical or horizontal beam spallation target. The proton beam is directed on a lead or lead-bismuth liquid spallation target, producing a neutron flux comparable to high flux test reactors.

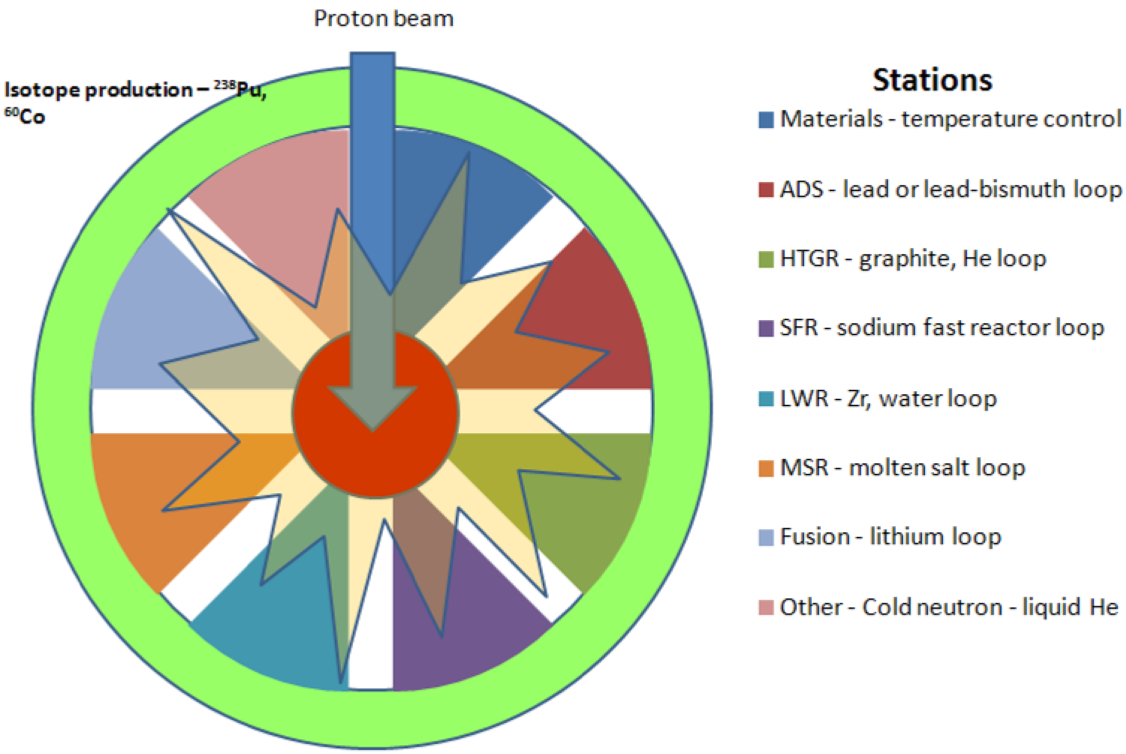


Figure 4.6. Nuclear Energy Station Concept

Table 4.1 summarizes the characteristics of the various potential Project X energy station modules. It is evident that this diverse range of environments will require careful design and implementation to be implemented in a single facility.

Table4.1 Project X Energy Station Test Modules Capabilities

Test Zone	Characteristics
General Materials Testing	Miniaturized specimens, Instrumented, controlled temperature, pressure Test materials compatibility, corrosion, radiation damage, aging, for unique environments
ADS Target loop	Lead or lead-bismuth flowing loop, on-line cleanup Test materials compatibility, corrosion, pin-type transmutation fuel and cladding tests
HTGR Module	Graphite structure, He coolant loop Test TRISO materials, pebble beds, fuel compacts
SFR Module	Sodium coolant loop, steel structure Test advanced high temperature long life materials, pin-type transmutation fuel and cladding tests
LWR Module	Pressurized water loop, LWR conditions, Test to address sustainability issues
MSR Module	Molten salt loop, Test materials compatibility, corrosion, dissolved fuel
Fusion Module	Lithium loop, Test radiation damage in materials, low activation materials, fusion blankets
Other Possibilities	Liquid He loop for cold neutrons, possible neutron beam extraction for nuclear data, measurement of integral cross sections, isotopic burnup, fission product yields

Isotope Production Module	Spectrum tailoring for specific isotopes, rabbit system for rapid insertion, moderators: D_2O, graphite, beryllium, metal hydride Beneficial use of leakage neutrons (^{238}Pu, ^{60}Co)

Table 4.2 shows the potential irradiation test volumes that might be available in a well designed energy station. Figure 4.7 shows that potential irradiation test volumes for the Project X Energy Station could be comparableto the volumes available in high power test teactors. Figure 4.8 shows a cross section of the neutron flux distribution for a test case of a cylindirical lead spallation target with a 3 GeV, 0.33 mA proton beam coming in from the top.

Table 4.2. Potential Test Volumes in the Project X Energy Station 1MW Concept

Neutron Flux Range	Dimensions 5 cm (R_1)	Available Test Volume
3e14-5e14	10 cm (R_2) x 50 cm (H)	~8 liter
1e14-3e14	40 cm (R_2) x 90 cm (H)	~270 liter
5e13-1e14	60 cm (R_2) x 110 cm (H)	~600 liter
1e13-5e13	100 cm (R_2) x 180 cm (H)	~2400 liter

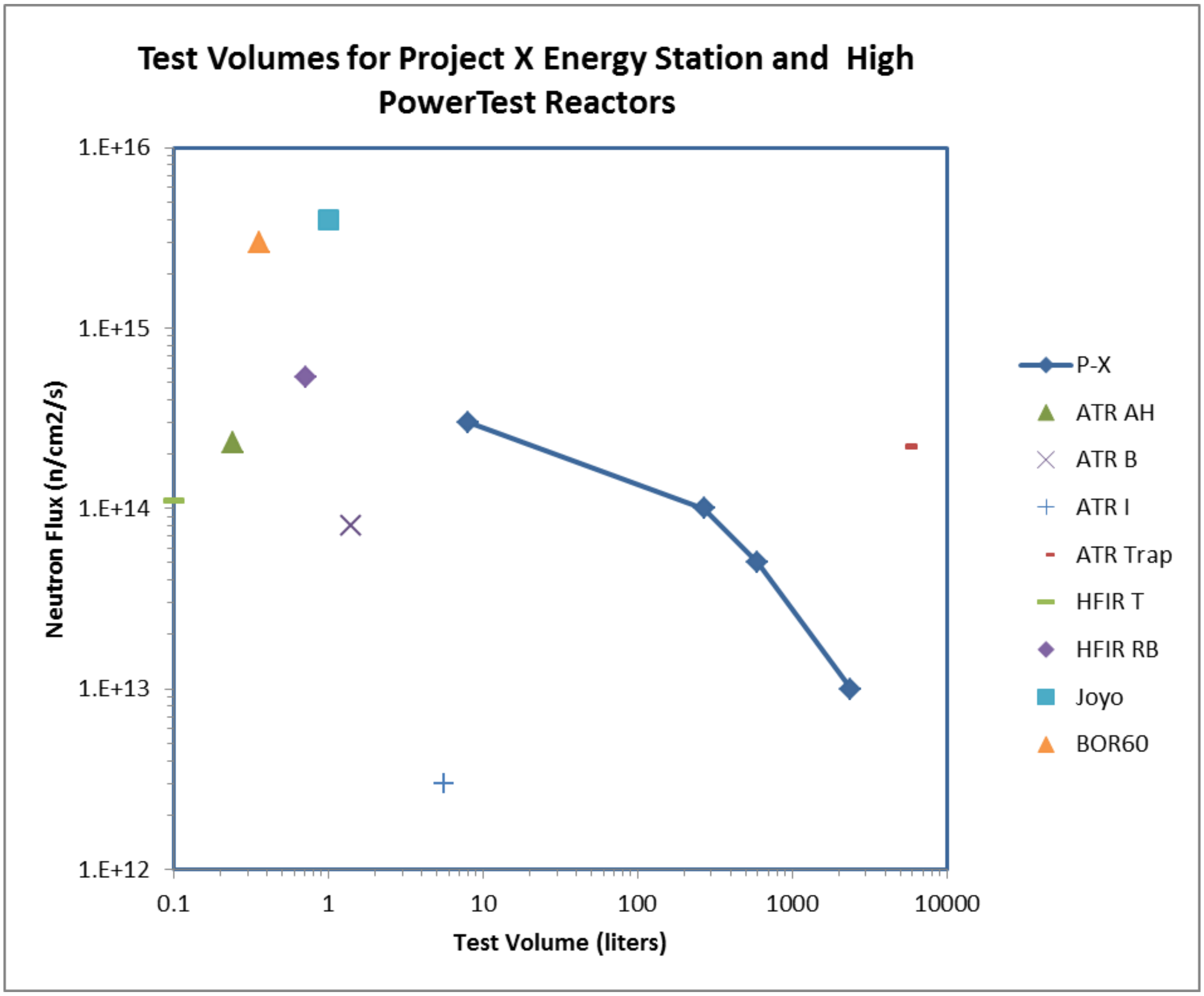


Figure 4.7 Potential Irradiation Test Volume for Project X Energy Station Compared to High Power Test Reactors

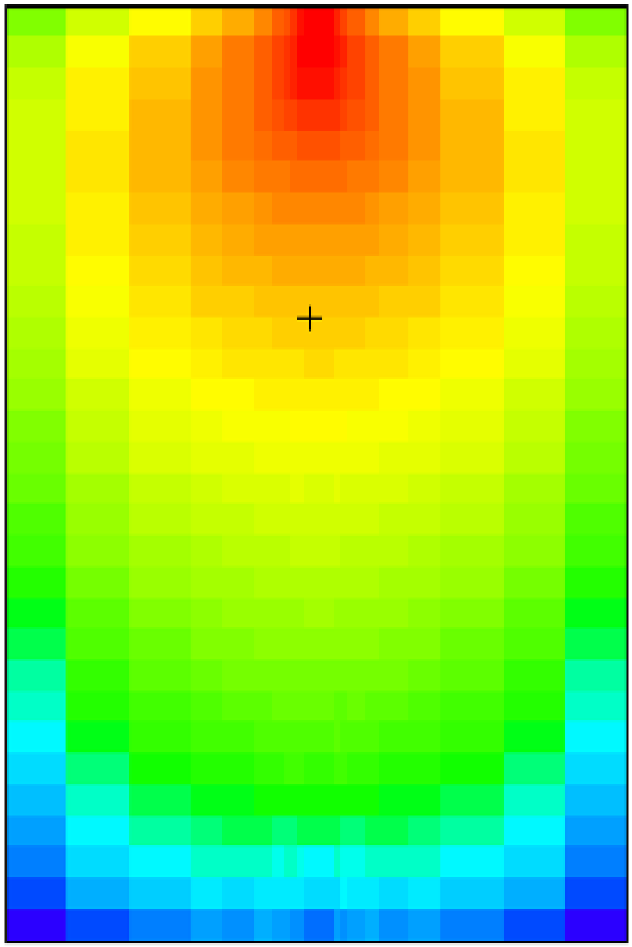


Figure 4.8 Cross section of neutron flux distribution for cylindirical lead spallation target with 3 GeV, 0.33 mA proton beam coming in from top (100 cm radius, 300 cm depth)

4.1 Effect of Proton Beam Energy (1 GeV vs 3 GeV)

The proton beam energy for the Project X Energy Station has not been decided, but both 1 GeV and 3 GeV options have been discussed. The 3 GeV beam energy may be more compatible with other High Energy Physics program needs and it would be preferable with respect to Project X costs. However, the 1 GeV beam energy option may be more prototypic of international accelerator driven systems (ADS) programs, and the Project X design has a provision to extract the beam at 1 GeV. The 1 GeV beam energy may be considered the favored option at the present time. A preliminary scoping evaluation considered a windowless lead spallation target with lead coolant arranged in a simple cylinder of 100 cm radius and 300 cm height with a proton beam of 1 MW beam power. Both 1 GeV and 3 GeV proton beam energies were compared with the total beam power fixed at 1 MW. For this beam power, with the beam energies and currents being considered, the peak neutron flux and the neutron flux distribution is nearly the same for different combinations of beam energy and beam current for the same beam power. The number of neutrons per source proton is inversely linearly proportional to the proton energy, but the product of the proton current and the neutrons per proton is nearly constant. The higher energy protons travel further into the spallation target, but the neutron production peaks in the first 30 cm of depth. The size of the spallation target could potentially be smaller at the 1 GeV proton beam energy.

- @ 3 GeV 105. neutrons/proton
- @ 1 GeV 32.4 neutrons/proton

Figure 4.9 compares neutron track distributions for a 1 Gev proton beam and a 3 GeVproton beam case for a 200 cm diameter by 300 cm high lead target. Figure 4.10 compares the radial neutron flux profile at the axial peak flux position for 3 GeV and 1 GeV proton beams. Figures 4.11 and 4.12 compare the axial neutron flux profiles for 1 MW proton beam at 3 Gev and at 1 GeV. Figure 4.13 compares the average neutron spectrum in the target region for a 1 GeV proton beam and a 3 GeV proton beam. This figure clearly shows that the neutron spectrum is essentially the same for the 1 GeV and 3 GeV proton beams, except for the high energy tail. The neutron spectrum will contain a high energy component up to the incident proton energy. Thus, with a 3 GeV proton beam, there will be some neutrons of up to 3 GeV, while with a 1 GeV proton beam, the highest energy neutron is 1 GeV. There is very little difference in the magnitude of the neutron flux as a function of the proton beam energy.

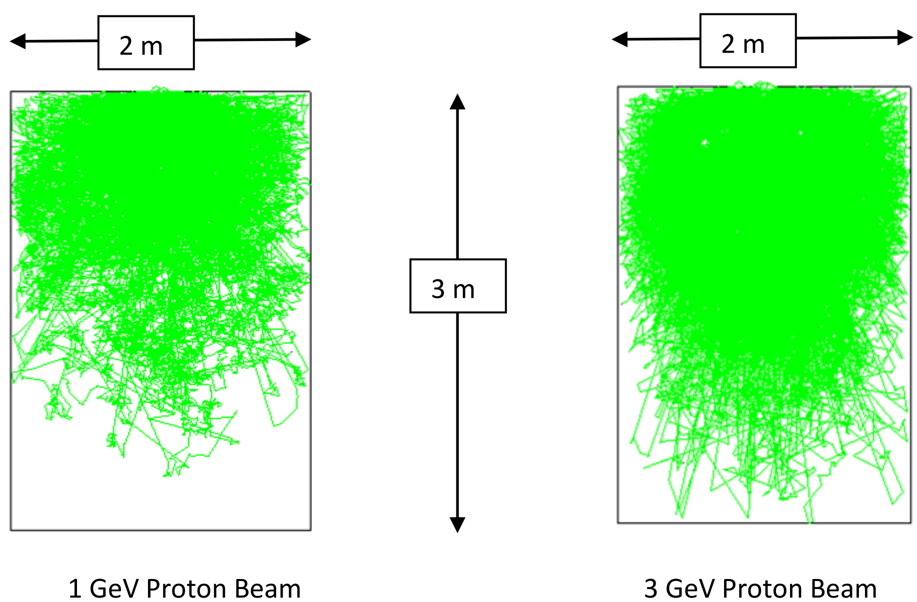


Figure 4.9 Comparison of neutron track distribution for 1 Gev proton beam and 3 GeVproton beam cases for 200 cm diameter by 300 cm high lead target. (Proton beam enters at top center)

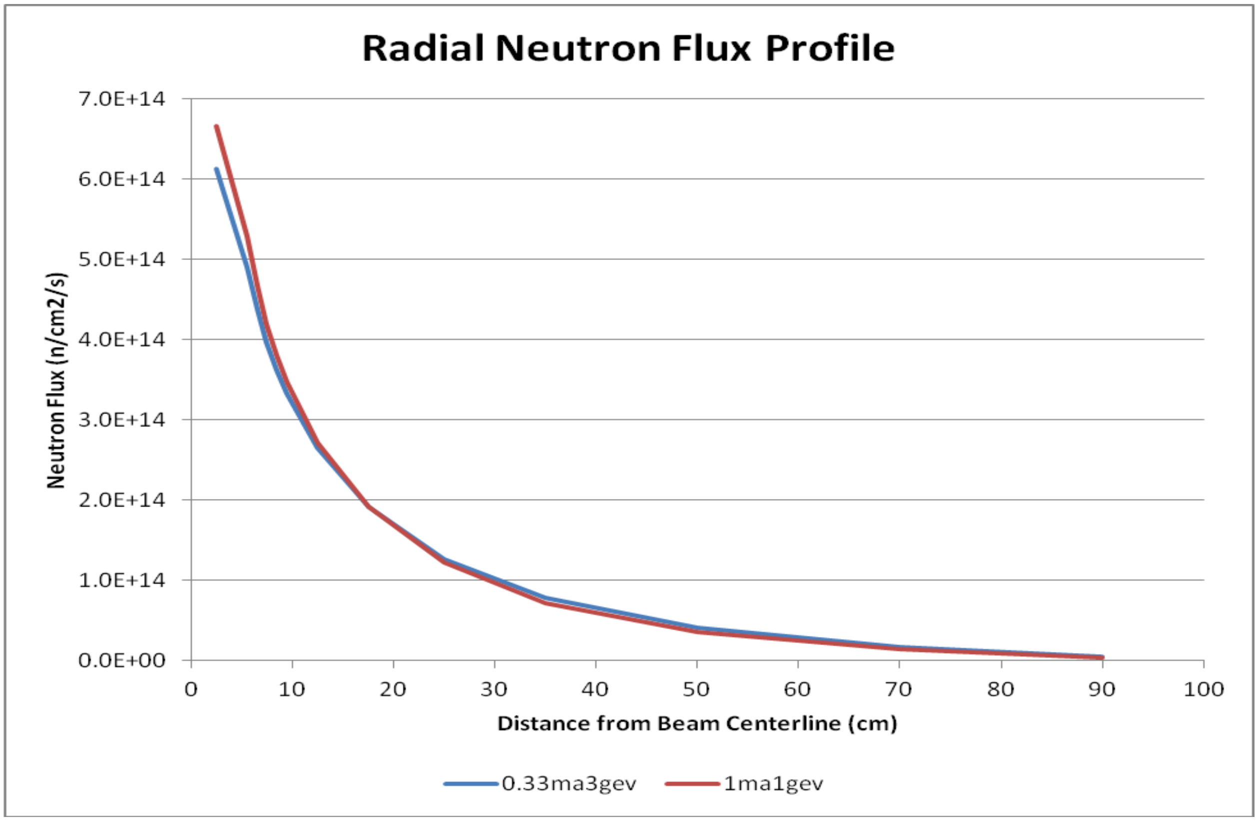


Figure 4.10 Comparison of radial neutron flux profile at axial peak for 3 GeV and 1 GeV proton beams

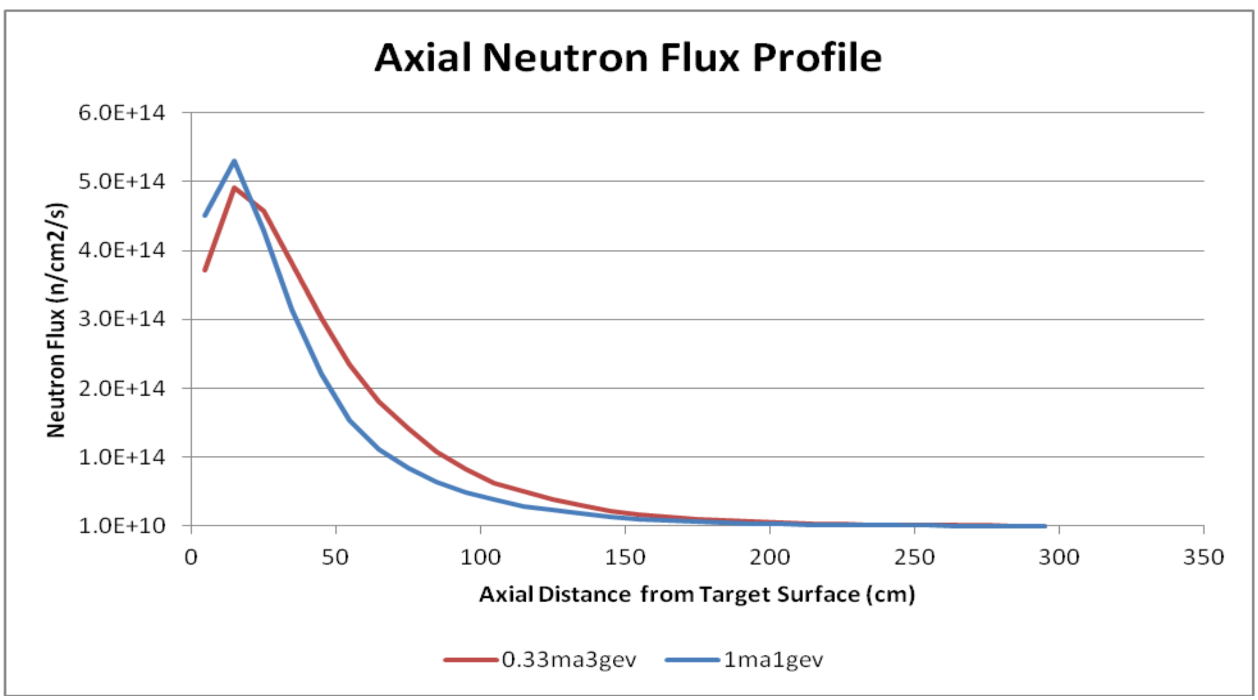


Figure 4.11 Comparison of axial neutron flux profile for 1 MW, 3 Gev and 1 GeV proton beams (linear scale)

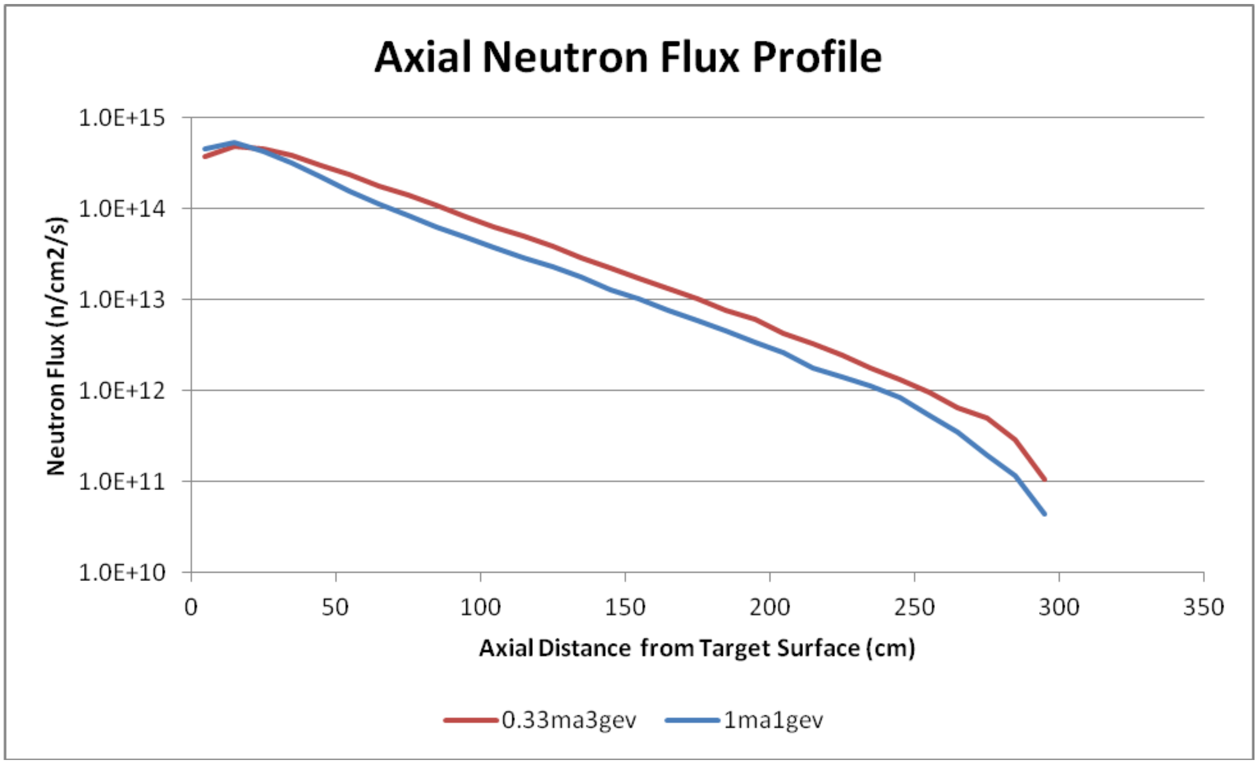


Figure 4.12 Comparison of axial neutron flux profile for 1 MW, 3 GeV and 1 GeV proton beams (log scale)

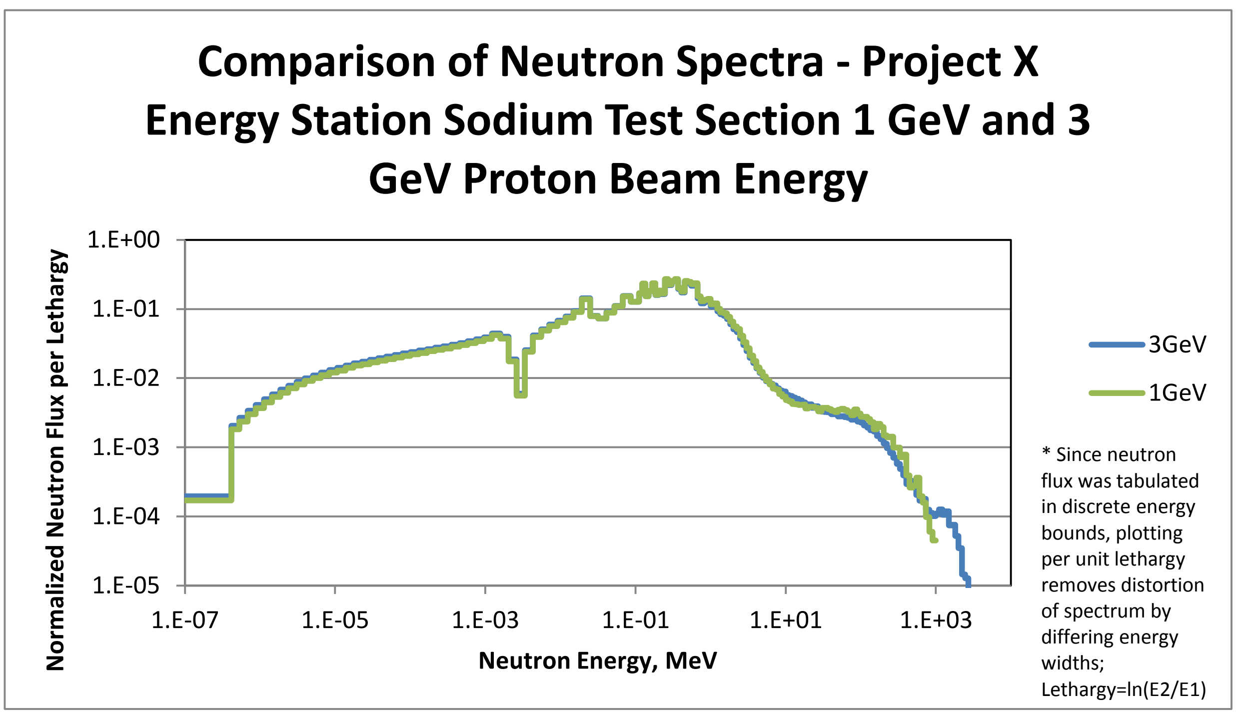


Figure 4.13 Comparison of neutron spectra in sodium test section for 3 GeV and 1 GeV proton beams

4.2 Comparison of Neutron Spectra in Energy Station Test Regions

Figures 4.14 through 4.21 compare example neutron spectra in the Project X Energy Station test regions with comparable typical reactor spectra for a sodium cooled fast reactor, lead cooled fast reactor, light water reactor, and a helium cooled graphite reactor. Note that the Energy Station test sections contain no fuel samples. Including test fuel pins will improve the comparison. These figures illustrate the following points:

- The unmoderated Energy Station neutron energy spectrum is very similar to a fast reactor spectrum over the energy range of most of the neutrons
- There are differences between the Energy Station spectrum and reactor spectrum at high and low energies, but these can be taken into account in interpreting irradiation testing results
- The low energy difference in the fast reactor comparisons is because there is no fuel in the Energy Station region (U-238 absorption will lower the neutron flux at lower energies)
- The high energy difference is from spallation neutrons generated up to the proton energy; this will create higher DPA rates and helium in samples, but may be an advantage in accelerating aging studies. Higher than prototypic helium production rates in test materials such as fuel cladding due to the high energy (>10 MeV) neutrons and other issues from the high energy tail have been evaluated in previous reviews of spallation sources for materials testing.
- There is very little difference in the neutron energy spectrum between 1 GeV and 3 GeV protons except for the high energy tail up to the proton energy

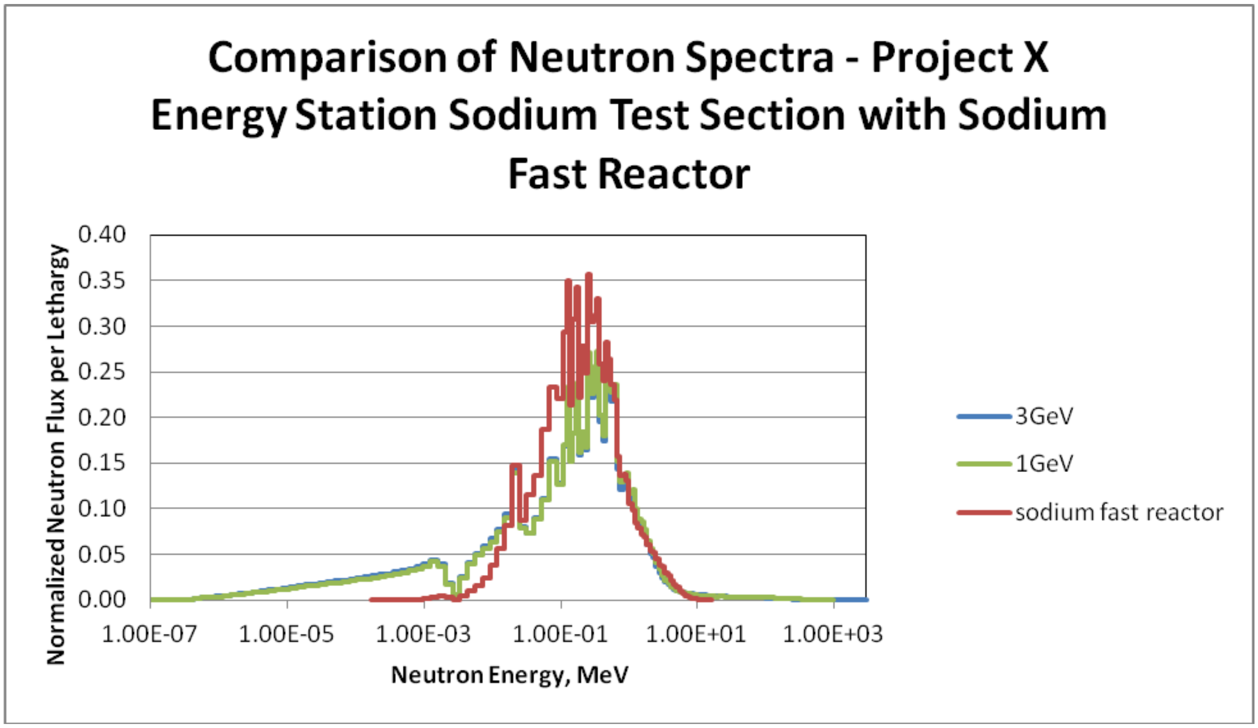
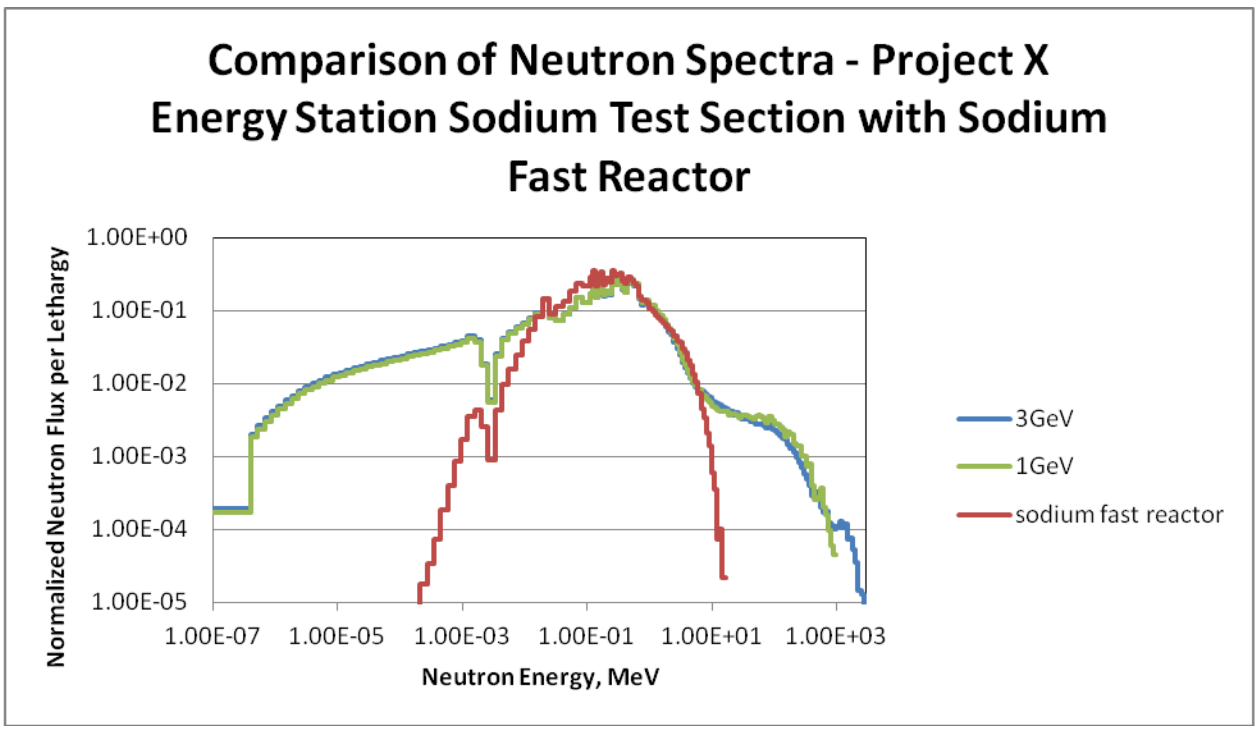
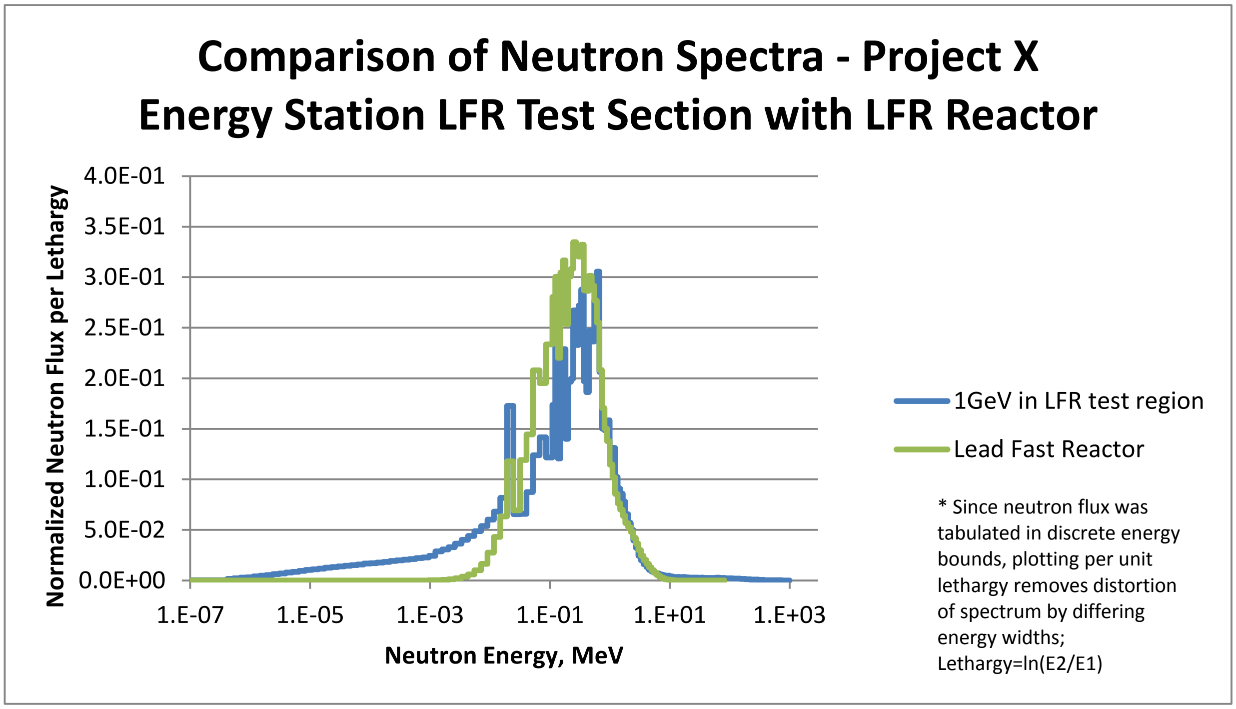


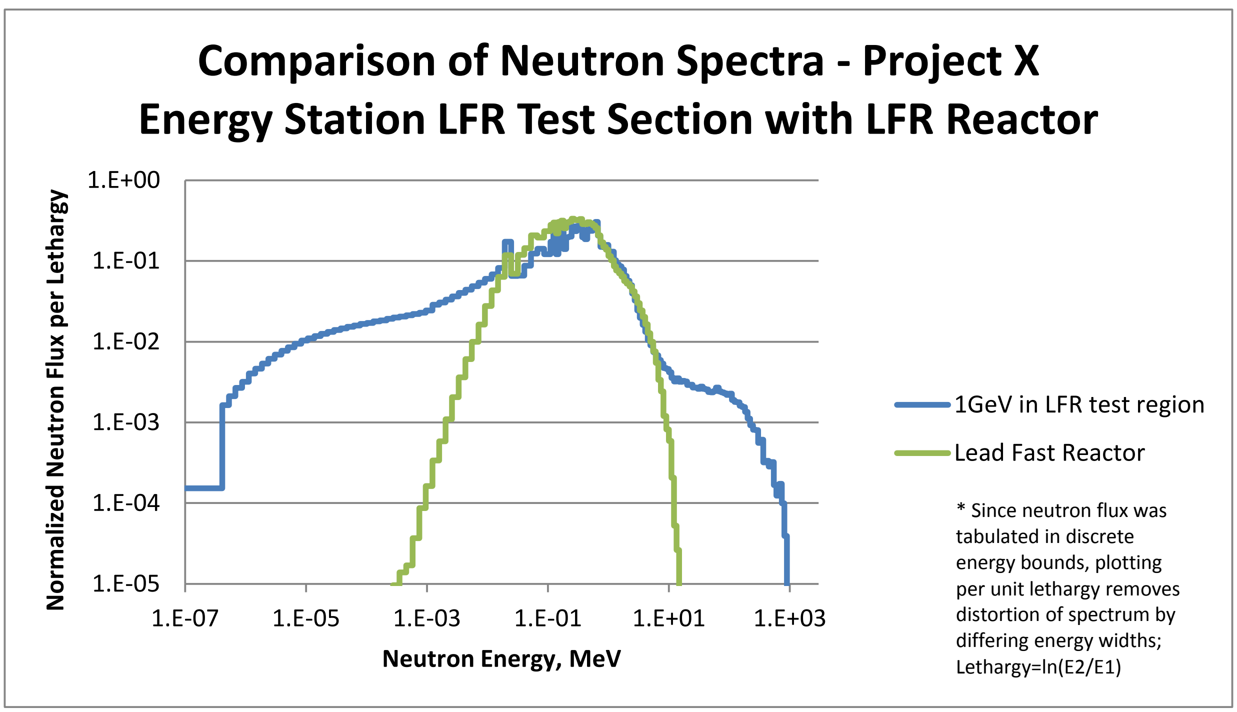
Figure 4.14 Comparison of neutron spectra in test section with sodium fast reactor



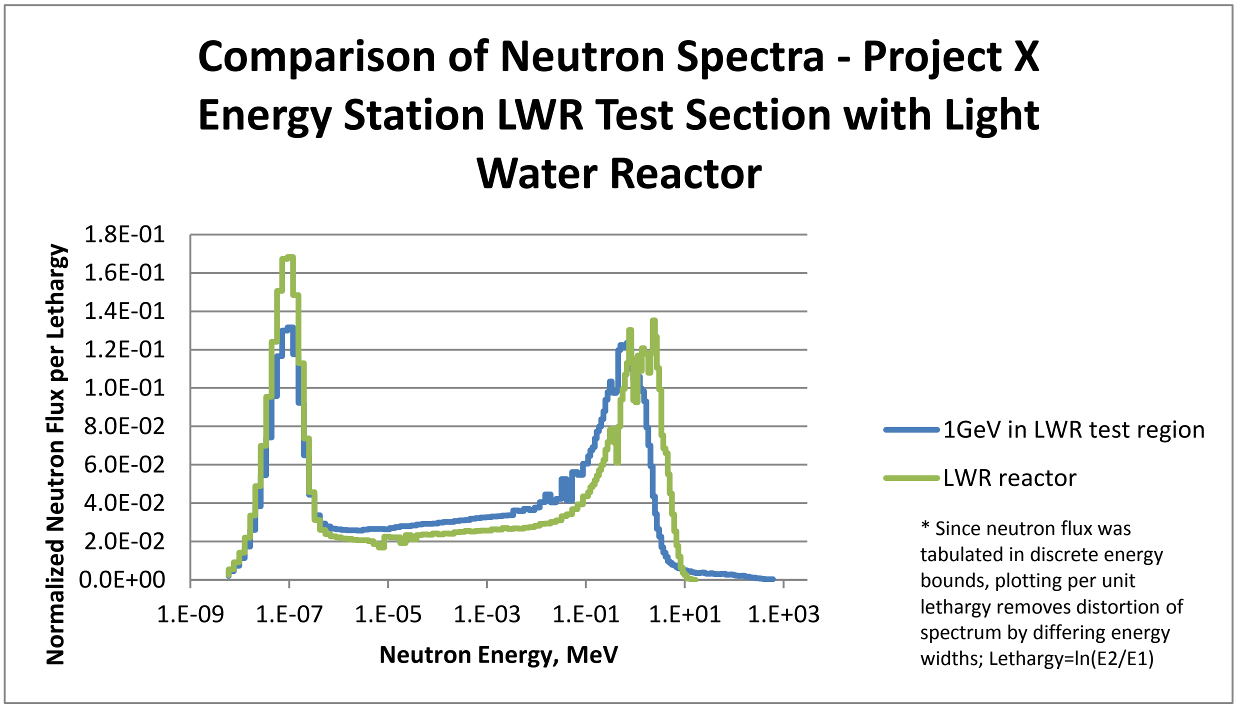
4.15 Comparison of neutron spectra in test section with sodium fast reactor



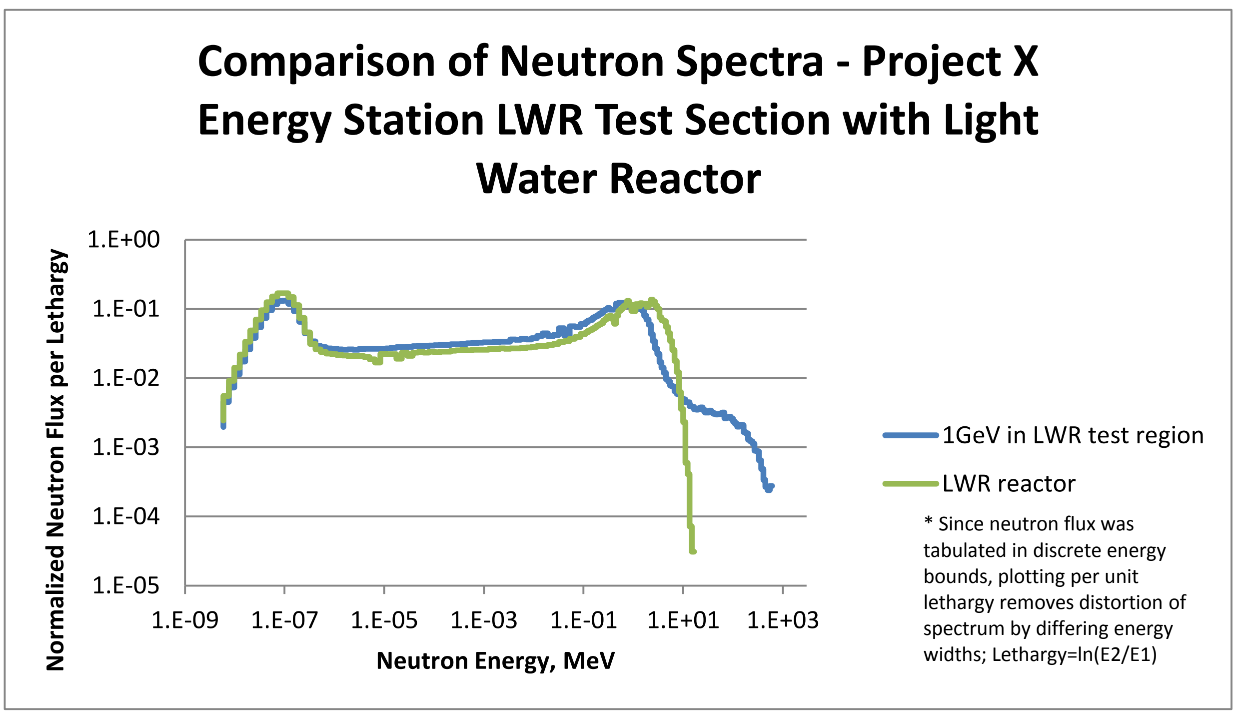
4.16 Comparison of neutron spectra in test section with lead fast reactor



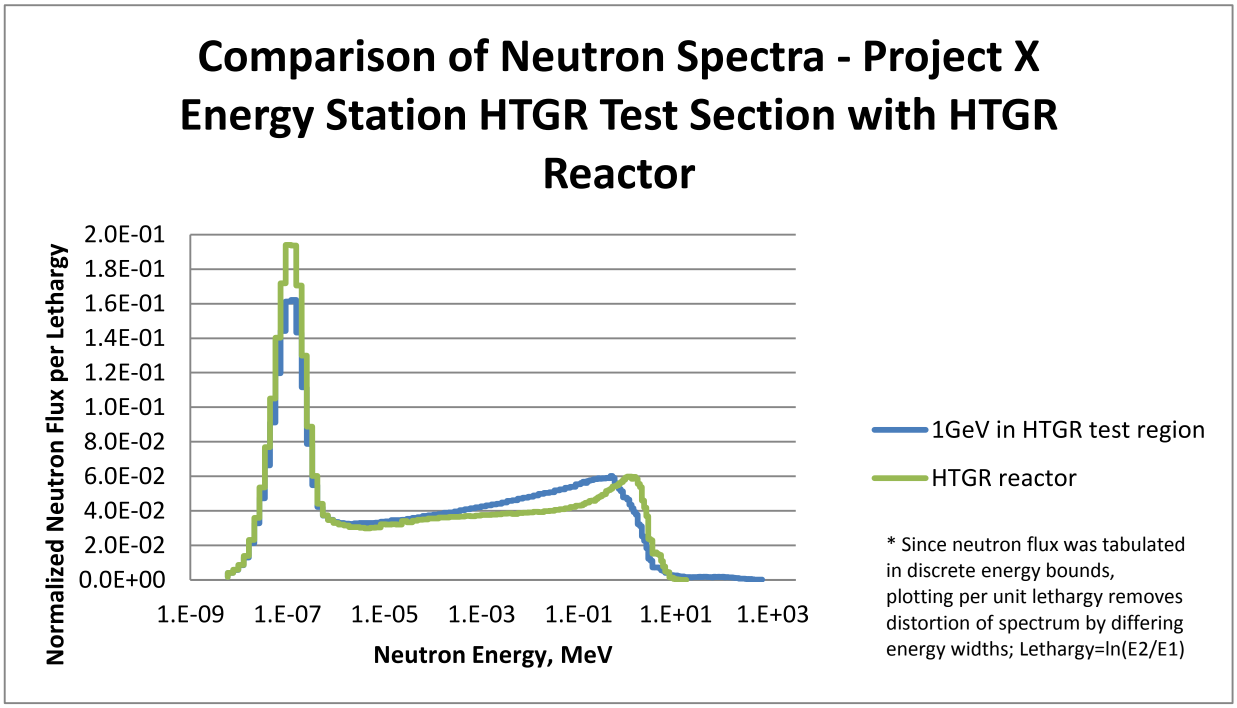
4.17 Comparison of neutron spectra in test section with lead fast reactor



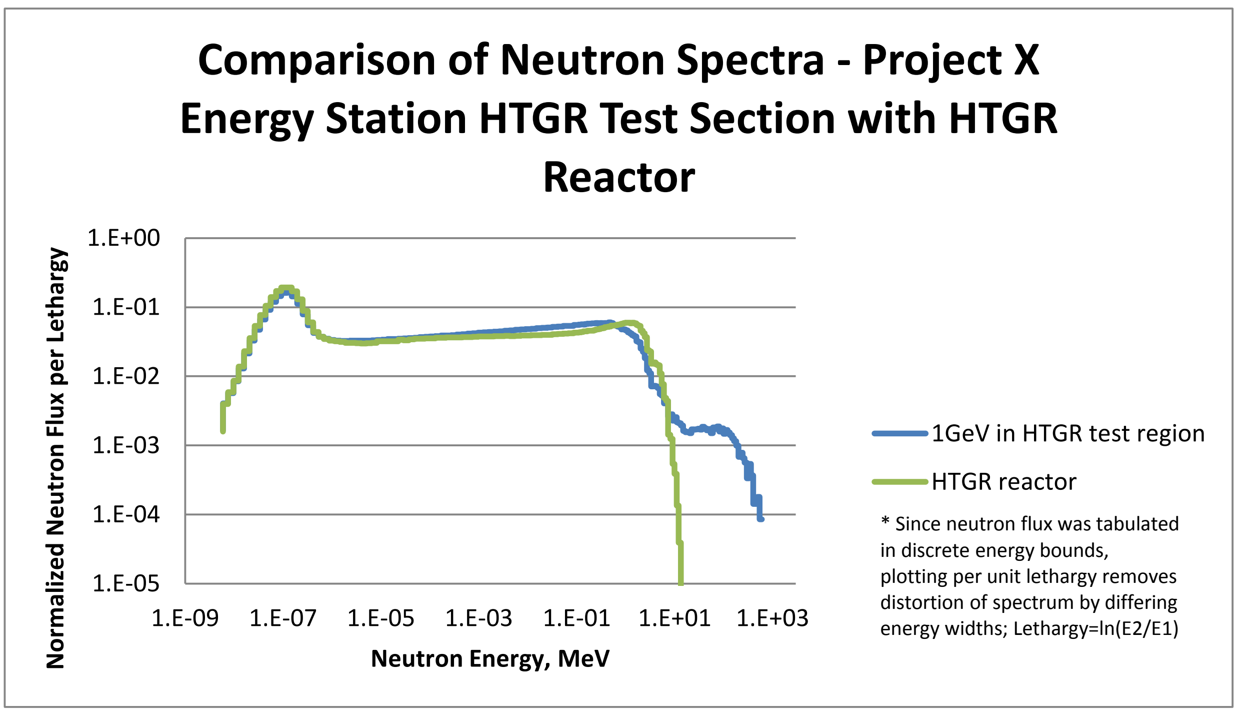
4.18 Comparison of neutron spectra in test section with light water reactor



4.19 Comparison of neutron spectra in test section with light water reactor



4.20 Comparison of neutron spectra in test section with HTGR reactor



4.21 Comparison of neutron spectra in test section with HTGR reactor

5 Capabilities of Project X Energy Station

5.1 National User Test Facility

The Energy Station could be structured as a National User Facility (NUSF) similar to what has been done at ATR. This would maximize collaboration between DOE, Universities, industry, and even allow foreign participation. Potential users would propose tests that would be evaluated by a committee. Utilization would also be open to international testing. The use of reconstitutable assemblies lessens testing costs, providing for a potentially broader utilization, especially by universities. The facility could grow to become a unique and valuable University educational resource for teaching as well as research.

5.2 Energy Station Test Facility Can Advance Technology Maturity

Materials are an immediate priority of both the fission and fusion communities. Extending the lifetime of the current fleet of light water reactors depends on understanding how the materials fail as they age. New generations of power reactors may operate at higher temperatures. New fuel types may be able to burn more efficiently, thereby extending the time between outages and extracting more energy from the fuel, thereby extending our energy resources. Fuel burnup in reactors is limited to about 20% primarily because the cladding mechanical integrity is reduced by radiation damage and elevated temperature. For fast reactor and fusion applications, helium accumulation from n,alpha reactions causes embrittlement. Table 5.1 lists some common materials issues for fission, fusion, and accelerator spallation facilities.

Table 5.1 Common Materials Issues for Fission, Fusion, and Spallation R&D

Materials Compatibility Issues	**Materials properties issues**	**Integrated performance issues**
• Coolant • Cladding • Target • Moderator • Transmutation products • Decomposition products • Thermal and Irradiation Stability Issues • Target material swelling • Cladding swelling • Moderator swelling • Target spalling • Irradiation damage effects • Chemical stability • Phase stability	• Thermal conductivity • Heat capacity • Melting point • Emissivity • High temperature strength • Creep behavior • Thermal expansion • Vapor pressure	• Effects of fission or transmutation product buildup • Stoichiometry changes during irradiation • Gas release • Thermal performance • Target material restructuring • Power-to-Melt behavior • Changes in properties with burnup • Fabricability • Target burn efficiency

For spallation neutron sources, there are some additional unique materials issues that could be addressed by the Project X Energy Station:

***In situ* Determination of Heat Transfer Properties and Degradation with Time**

Spallation neutron source target, moderator, reflector, and shield configurations are complex in terms of geometry and function. Because heat generation in spallation neutron source components is internal due to energetic particle interaction with electrons and atoms, simulated laboratory heat transfer measurements are difficult. A test bed such as the Project X Energy Station with a prototypic radiation environment provides the necessary heat generation and allows for the determination of the heat transfer characteristics. As materials change dimension because of radiation exposure, and as corrosion products deposit on surfaces, heat transfer characteristics can change. The Project X Energy Station can be an effective test bed for determining the magnitude of these changes along with any changes in coolant chemistry.

Development of Surveillance Methods and Monitors of System Performance

Knowledge of the status of equipment in operation enables intelligent decisions to be made regarding the need for replacement or repair of a component. Such information is essential for any maintenance program in order to be able to provide reliable operations. In spallation neutron source environments, any monitor of system performance will be exposed to particle or electromagnetic radiation and thus suffer possible degradation. The proposed test bed offers an opportunity to systematically test surveillance equipment, which may be similar to surveillance equipment being developed for LWR aging studies. Areas of concern include temperature and flow measurements, coolant chemistry measurements, and behavior of materials irradiated during the operation of a facility. The inspection of liquid metal spallation target material can measure of the performance of the system, especially in terms of corrosion.

Contamination of Fluid Systems with Transmutation Products

Corrosion and spallation products are generated in the beam path and enter coolant systems at spallation neutron source facilities. Radioactive contaminants must be effectively trapped in filters so the contaminants can be properly handled and disposed. The test bed offers an opportunity to develop this type of equipment and procedures.

Mechanical Properties Degradation

The effects of atomic displacements in materials exposed to particle radiation are accelerated when impurities are introduced along with the displacements. Spallation neutron source environments contain more energetic particles than fission reactor environments. This more energetic environment causes displacements and transmutation product impurities. Data from fission reactor experience can be used only as a guide since impurity production in fission reactor environments may be 10 to 100 times less than in spallation neutron source environments. A database of information concerning materials radiation damage effects in spallation neutron source environments can be generated in both the proton beam and the energetic spallation neutron flux. The test bed provides the proper environment for testing the long-term exposure of such materials under controlled conditions.

Dimensional Stability
In spallation systems, displacement damage and production of gases such as helium lead to nucleation and growth of interstitial dislocation loops, voids, and gas bubbles in the material microstructure. After extended exposure, macroscopic dimensional changes can occur. The magnitude of dimensional changes in candidate spallation neutron source materials needs to be determined and resistant materials need to be identified. A test bed that has a spallation neutron source prototypic environment is essential for conducting these studies.

Comparison of Spallation Neutron Source Performance Data to Fission Reactor Data
Comparative studies of material property changes between fission reactor, spallation neutron, and proton irradiations would enhance the ability to determine whether the fission reactor materials database can be applied to spallation neutron source applications. A test bed with a spallation neutron source environment where controlled experiments at high radiation dose can be performed is essential for these comparative studies.

Basic Understanding of Atom Displacement Physics at High Recoil Energies
Radiation damage and radiation effects calculations are used to predict the details of displacement cascades and microstructural evolution. Accurate measurements of point defect production rates and other basic data in spallation neutron source environments can improve these calculations. These measurements require a test bed with prototypic spallation neutron source radiation environments.

Basic Understanding of Transmutation Product Morphology and the Effect on Properties
Atoms formed from spallation transmutation reactions enter a metal alloy system as an impurity. The subsequent diffusion and reaction history, as well as the final fate of the impurities, are dependent on radiation rate, temperature, energy of atomic recoils, and other factors such as grain size. Development of alloys that can resist the detrimental effects of impurities requires first a basic understanding of the kinetics and chemistry of the governing processes during irradiation. Work in this area using a test bed with the proper radiation environment may lead to development of low activation, low neutron absorbing, and thermally stable alloys for use at spallation neutron sources.

5.3 Comparison of Project X Energy Station with Other High Power Proton Accelerator Facilities

The proposed Project X energy station will be a unique test facility for performing irradiation testing to support nuclear energy program needs. The high power proton beam will produce a neutron flux that is comparable to large fast neutron flux test reactors. Careful design can likely provide multiple unique testing environments adapted to specific nuclear energy testing needs that would be extremely difficult to provide otherwise. A flexible design should be able to do the materials testing to demonstrate the feasibility of improvements to existing technologies as well as demonstrate the feasibility of several advanced concepts that otherwise could not be tested without constructing major new test facilities.

Although there are several existing and planned accelerator facilities that produce MW level beam powers, none can provide the flexible testing environment envisaged in the energy station concept described here. Many are operated in a low duty cycle pulse mode (MTS/MaRIE, ESS, SNS, J-PARC, HP-

SPL) which can be difficult to maintain constant irradiation conditions. Others do not provide for materials irradiation testing since they are designed as beam facilities (SNS, ISIS). Table 5.2 shows a comparison the Project X energy station accelerator with other existing and planned proton accelerator facilities. Both the 1 GeV and 3 GeV concepts for the Project X accelerator are shown, since they span the range of beam parameters envisioned for the facility. The Project X beam power of 1 MW was maintained constant for these concepts. The selection of beam power and current will be done after further studies of tradeoffs regarding the impact on target size and accelerator beam complexity. Figure 5.1 plots the beam current versus beam energy at the target for these accelerators and also shows the duty factor and irradiation test volume. Figure 5.2 compares the irradiation test volume as a function of the neutron flux level for the Project X energy station versus the largest competing accelerators. Figure 5.3 shows the same comparison but includes the large test reactors.

The configuration and design of the Project X energy station is still at a pre-conceptual level, and additional work is recommended to evaluate the following fundamental parameters that can significantly affect the layout of the target station:

- Vertical versus horizontal proton beam alignment on spallation target
- Beam window or windowless spallation target design
- Solid rotating spallation target versus liquid heavy metal target
- Beam energy and current selection (for example, 1 mA-1Gev to 0.33 mA 3GeV)
- Limiting beam power density -beam diameter or beam rastering over larger surface

Table 5.2. Proton Accelerator facilities

Facility	Initial Operation	Current	Energy	Beam Power	Mode	Peak n flux n/cm2/s	High flux volume	Peak dpa rate Dpa/y	He/dpa H/dpa ratio
Project X Energy Station Options	2021	0.33mA	3 GeV	1 MW	CW >50%DF	2e15	8L >3e14 300L >1e14		
		1 mA	1 GeV	1 MW	CW >50%DF	2e15			
MYRRHA 85MWt Accelerator driven subcritical system (ADS) Pb-Bi spallation target Pb-Bi coolant Fast spectrum	2018	2.5 mA	600 MeV	1.5 MW	CW linac				
MEGAPIE – PSI Pb-Bi spallation target		1.5 mA	590 MeV	0.8 MW	CW				
SINQ – PSI	1996			1.2 MW					
MTS – LANL Tungsten spallation target (dual) with Tantalum front face Pb-Bi or D_2O coolant	2015	1.25 mA	800 MeV	1 MW	Pulsed <10%DF	1.6e15	0.2 L 0.45 L	7.5-17.5 2.5-7.5	8-13
MaRIE – LANL MTS with in situ diagnostics using x-ray scattering			800 MeV	1.5 MW	Pulsed 12%DF	2e15			
SNS – ORNL Liquid mercury spallation target (6% duty factor)	2006	1.4 mA	1 GeV	1.4 MW	Pulsed 6% DF				

SNS upgrade – ORNL		2.3 mA	1.3 GeV	3 MW	pulsed				
China		10 mA	1.5 GeV	15 MW					
China		10 mA	1 GeV	10 MW					
JPARC TEF-T – JAEA Liquid mercury spallation target for ADS	~2015	0.3 mA	600 MeV	0.2 MW	Pulsed 1.25%DF				10
JPARC-TEF-P – JAEA Critical assembly for ADS				10 W					
ESS – Sweden Spallation source Liquid mercury spallation target	2018	50 mA	2.5 GeV	5 MW	Pulsed 5%DF	6.5e14 2.2e15 T 1.2e15 R	0.4 L target 5 L reflector	5-10, 20-50	10 40
XADS Subcritical ADS Pb-Bi target/coolant		2.5-4 mA	600 MeV	1MW		1.2e15		38	35 430
India		2.0 mA	1 GeV	2 MW					
India		10-30 mA	1 GeV	10-30 MW	CW SRF linac				
ISIS – UK Synchrotron For neutron scattering and basic research		0.2 mA	800 MeV	0.16 MW	Pulsed 2.5%DF				
Triumf		0.2 mA	520 MeV	0.10 MW	CW				
HP-SPL	2020	0.8 mA	5 GeV	4 MW	Pulsed 6%DF				

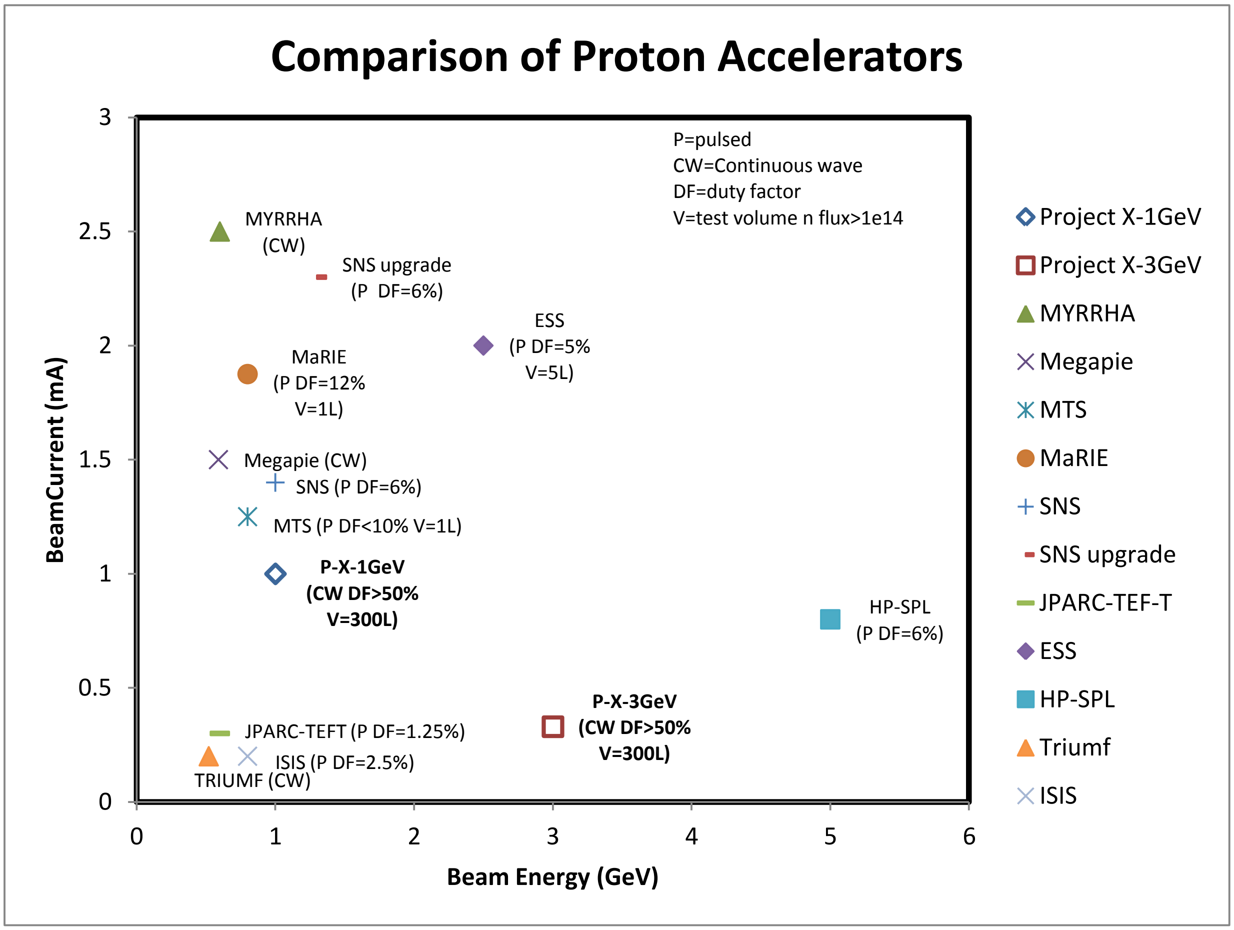


Figure 5.1 Comparison of Project X Accelerator Energy Station with Existing and Planned Proton Accelerators for beam energy, beam current, irradiation test volume, and duty factor

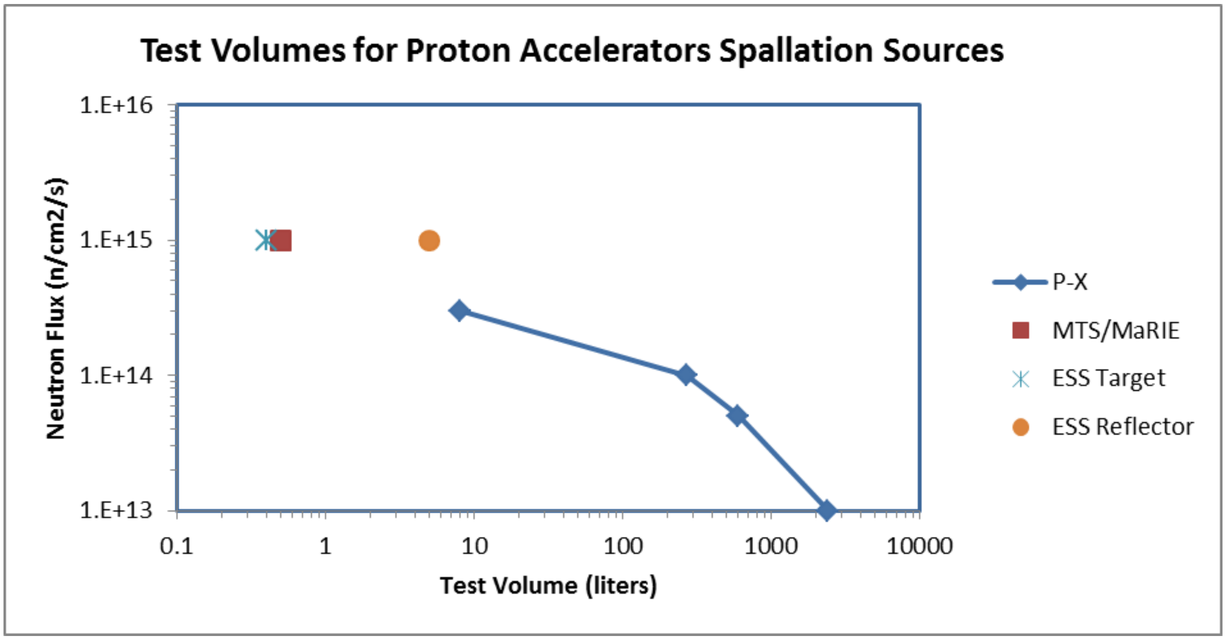


Figure 5.2 Comparison of Project X Energy Station with Other Large Accelerators in terms of irradiation volume at various neutron flux levels

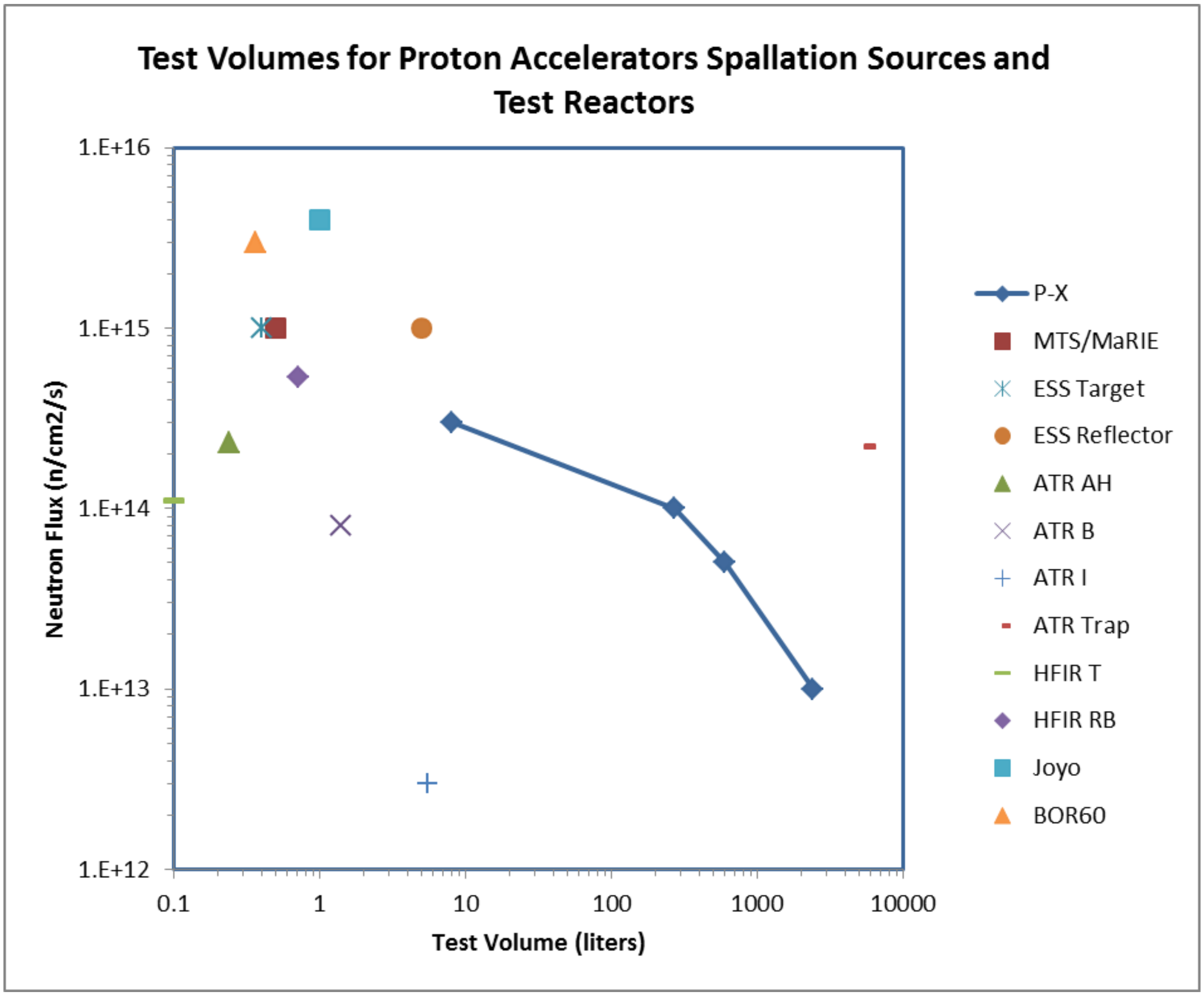


Figure 5.3 Comparison of Project X Energy Station with Other Large Accelerators and Test Reactors in terms of irradiation volume at various neutron flux levels

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Appendix

PNNL Experience Base and Capabilities

Figure A1. PNNL Capabilities and Experience Can Support Project X Energy Station Concept Development

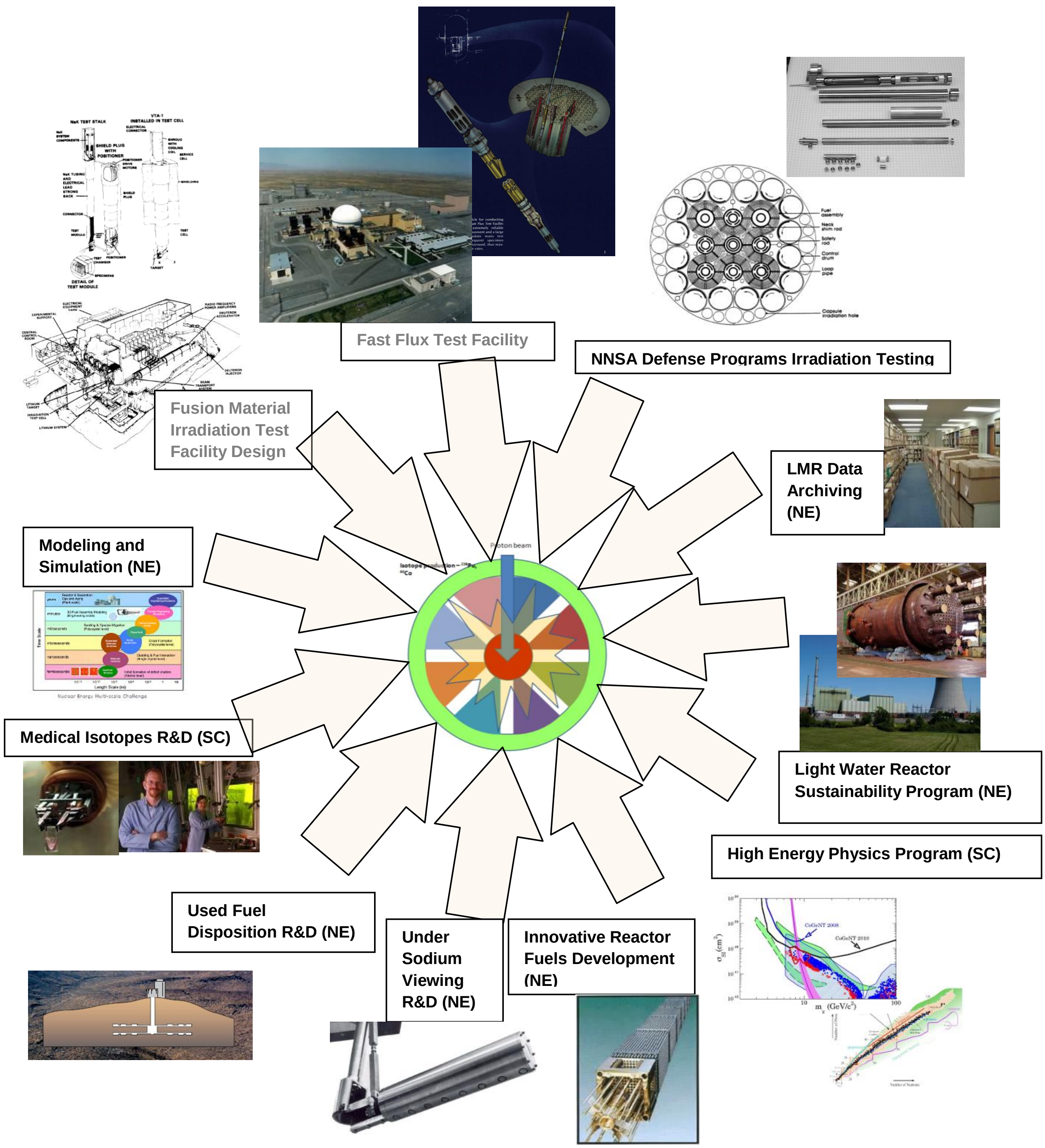
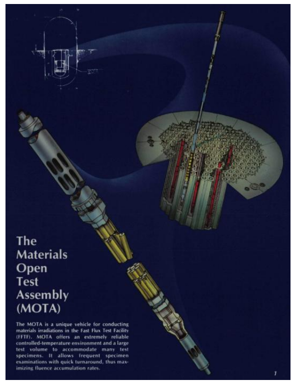
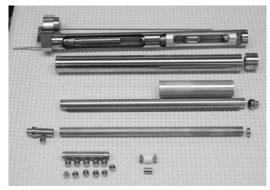


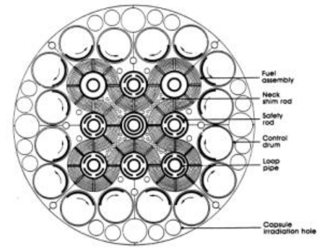
Figure A2. PNNL Participation in Past and Current DOE NE Programs Provides Experience Base for Developing Project X Energy Station Concept

Fast Flux Test Facility



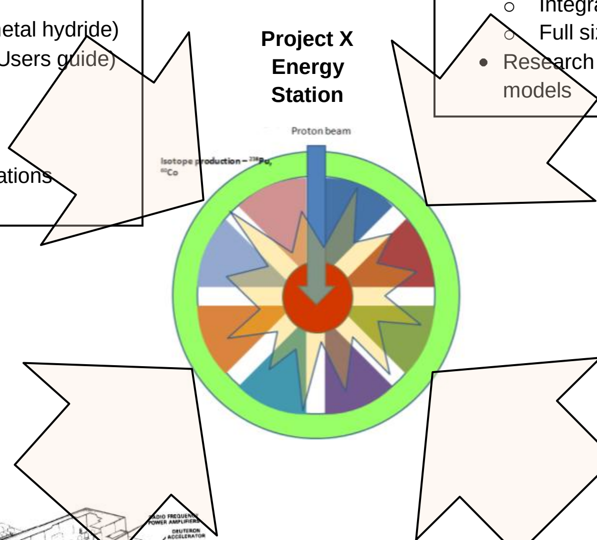
NNSA Defense Programs Irradiation Testing



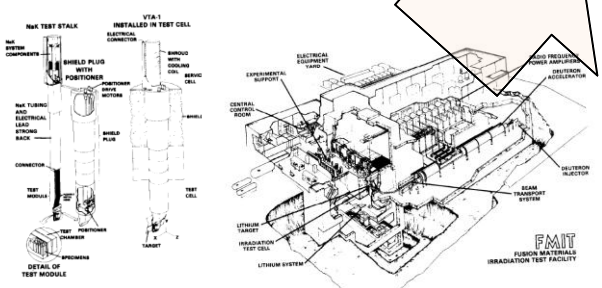


Fast Flux Test Facility
- Liquid metal technology (Na, NaK)
- Reconstitutable test assemblies
- International, Multi-program irradiation testing
  - LMR fuels and materials
  - Fusion blanket and materials
  - Beneficial isotope production
  - Space Power
  - Materials
  - Waste transmutation
  - Neutron spectrum tailoring (metal hydride)
- Irradiation test design interface (Users guide)
- Hot cell for reconstitution, remote manipulators, shielding
- Independent closed loop design
- QA program, Fabrication specifications
- Under sodium viewing capability

NNSA Defense Programs Irradiation Testing
- Design, development, analysis, fabrication of tests
- Performance predictions, test planning
- Irradiation testing in ATR,
- Post irradiation examination
- Interpretation of results
  - Basic tests
  - Separate effects tests
  - Multiple effect tests
  - Integral tests
  - Full size verification
- Research program for improving performance models

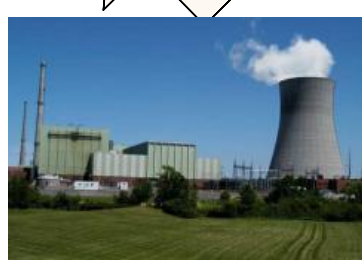


Fusion Material Irradiation Test Facility Design



Fusion Materials Irradiation Test Facility
- Accelerator target station design
- Shielding, remote workstations
- Reconstitutable test modules
- Independent test module cooling
- Miniaturized test specimens
- Fusion materials testing needs
- Value of full-scale mockups
- Liquid metal technology (Li, NaK)
- Windowless liquid metal target deign
- Comparable beam power

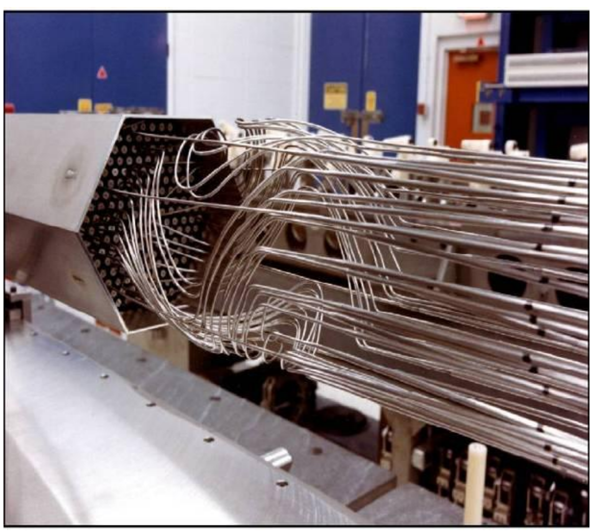
Light Water Reactor Sustainability Program



LWR Sustainability Program
- Materials Aging and Degradation
- Risk-Informed Safety Margin Characterization
- Efficiency improvements
- Advanced Instrumentation and Controls
- Advanced Fuel Development
- Online monitoring/diagnostic capability
- In-pile instrumentation

Fast Flux Test Facility (FFTF)

- 400MWth sodium cooled fast spectrum test reactor
- Instrumented test assemblies
- Reconstitutable test assemblies
- Tests supported materials development, advanced reactor, transmutation, isotope production, space reactor, fusion, nuclear data
- IEM cell - world's tallest hot cell for examination, reconstitution, and maintenance
- Liquid metal expertise – EM pumps, corrosion, cold traps for purification



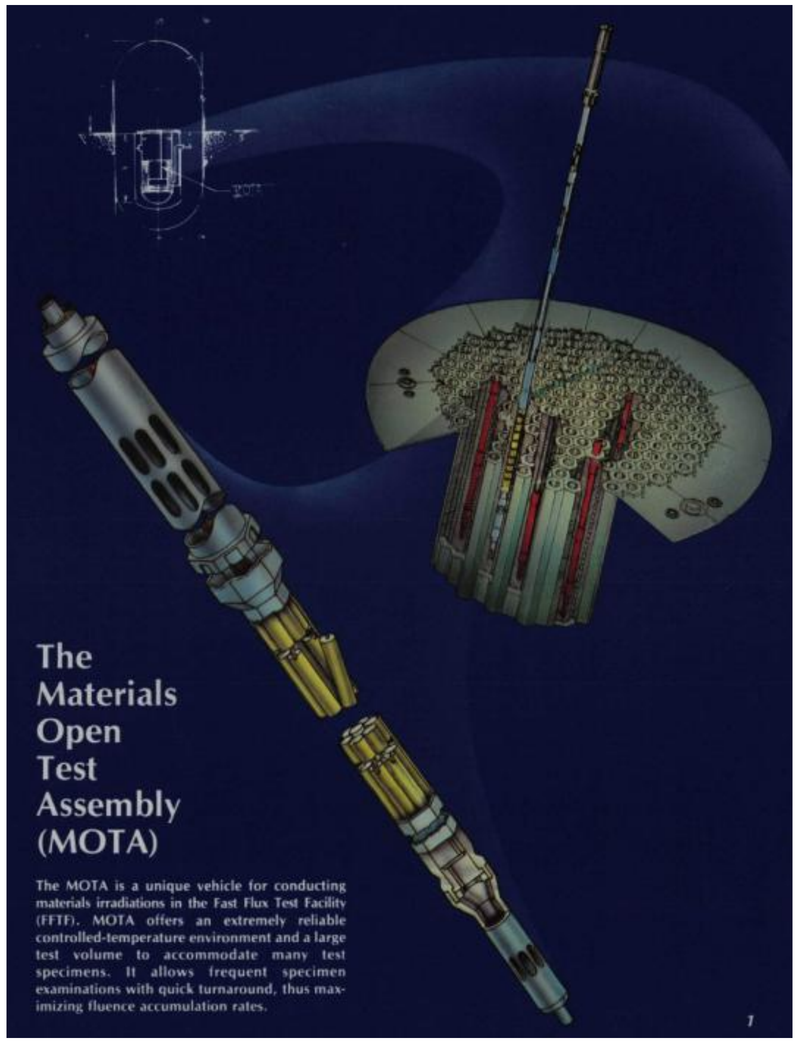


Figure A3 FFTF Test Assemblies

Fusion Material Irradiation Test (FMIT)

- 35 MeV, 100 mA Deuteron accelerator on windowless flowing lithium metal target
- US facility designed in 1980's for fusion material irradiation tests.
- Detail design and supporting tests completed and ready for construction when funding cut
- Test assembly region designed for thousands of miniature material test specimens in one test
- 3.5 MW beam energy deposited in target (2 MW/cm^3)
- 740 °C peak lithium temperature
- 33 liters/second flow rate
- Preserved Detailed design information such as drawings, fabrication specifications, are retrievable

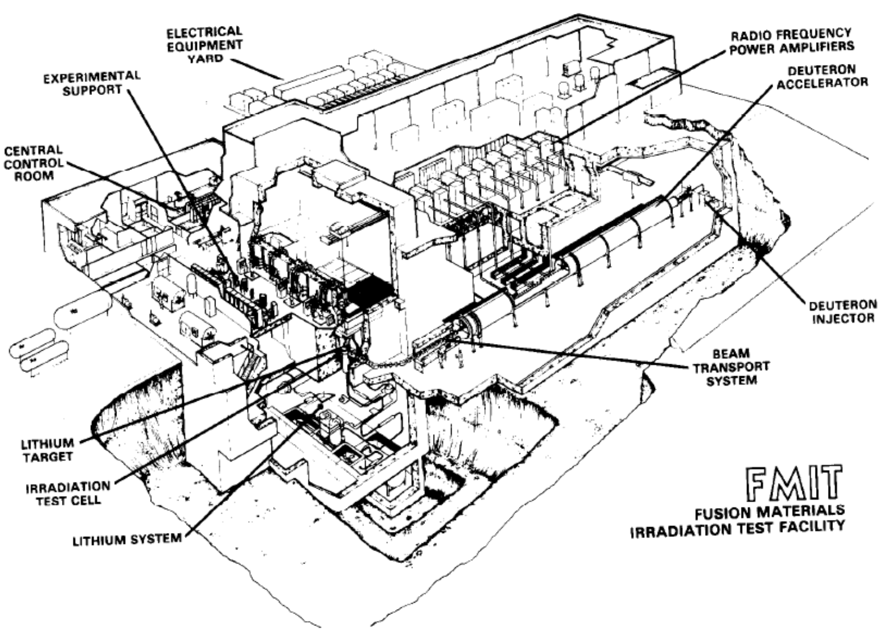
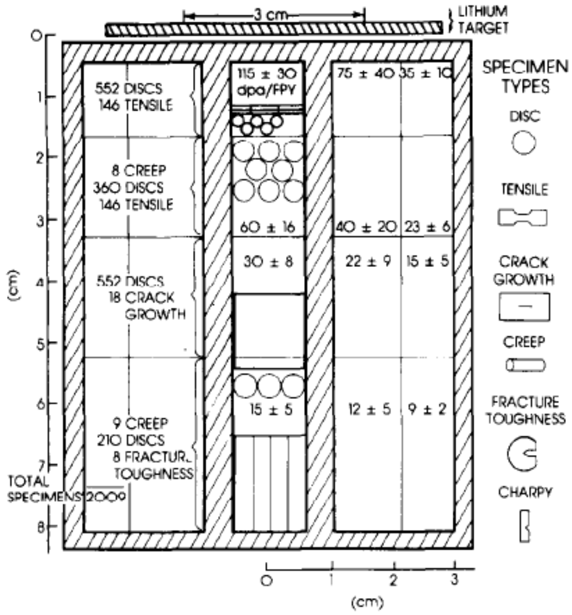


Figure A4 Fusion Materials Irradiation Test Facility (FMIT)



TEST TYPE	FLUENCES (dpa)	TEMPERATURE (NO.)**	SPECIMENS
TEM DISCS (C.M.)	5-100	4	2400
TEM DISCS (F)	5-100	3	450
TENSILE (POSTIRRADIATION)	5-100	3	240
CREEP RATE	TO 100	3	30
BEAMS (MULTIPURPOSE)	5-50	3	90
TEM DISCS (M)	2-10	4	1800
TEM DISCS (C)	2-10	4	2160
TEM DISCS (F)	2-20	3	2160
CREEP/RUPTURE	TO 50	3	225
STRESS RELAX (IN SITU)	3 PREIRRAD.	3	270
BEAMS, PREIRRAD.	2-10	3	180
TENSILE (POSTIRRAD. AND DISPENSATION)	5-50	3	1080
IN SITU CYCLIC STRESS (M)	5-50	3	180
ALT MAT'LS (M)	2-10	2	360
ALT MAT'LS (POSTIRRAD. MECH/ELEC)	2-10	2	360
IN SITU CYCLIC FLUX	5-50	3	180
TEM DISCS	0.2-5	3	680
TEM DISCS (CORRELATE TO RTNS-II)	0.2-2	3	180
TEM DISCS (SEED MICROSTRUC)	0.2-2	3	810
CREEP RATE	TO 5	3	30
TENSILE (SEED MICROSTRUC)	0.2-2	3	810
			14,575

*C-CHEMICAL ANALYSIS OF TRANSMUTATION EFFECTS
M-MICROSTRUCTURAL EVOLUTION EVALUATION
F-DEFORMATION FLOW PROPERTIES BY HARDNESS TESTS
**TEMPERATURES OVER RANGE OF 50-650°C

Figure A5. Example of FMIT High Flux Region Test Matrix

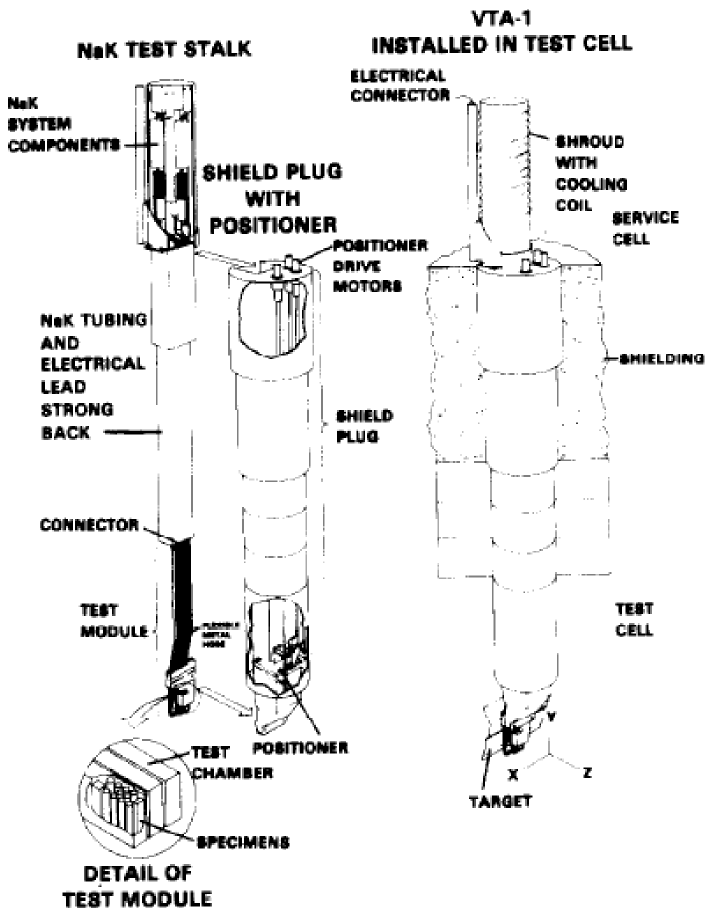


Figure A6. FMIT Vertical Test Assembly

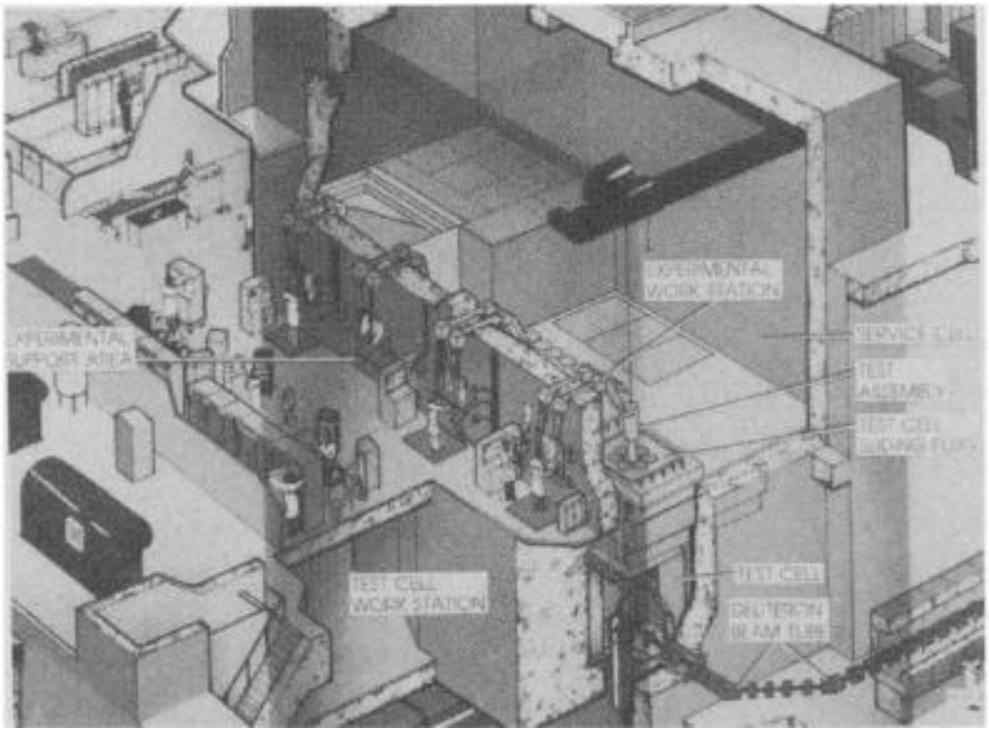


Figure A7. FMIT cutaway showing operating floor and remote handling equipment

FMIT Lithium Test Loop

- Full-Scale Mockup of FMIT lithium system was constructed and operated at Hanford
- 16,000 hours of safe reliable operation
- Demonstrated satisfactory performance of system components: EM pump, target, purification and characterization systems, chemistry systems, argon systems, vacuum systems
- Tested instrumentation, coolant chemistry, vapor/aerosol transport, corrosion
- Testing reports retrievable

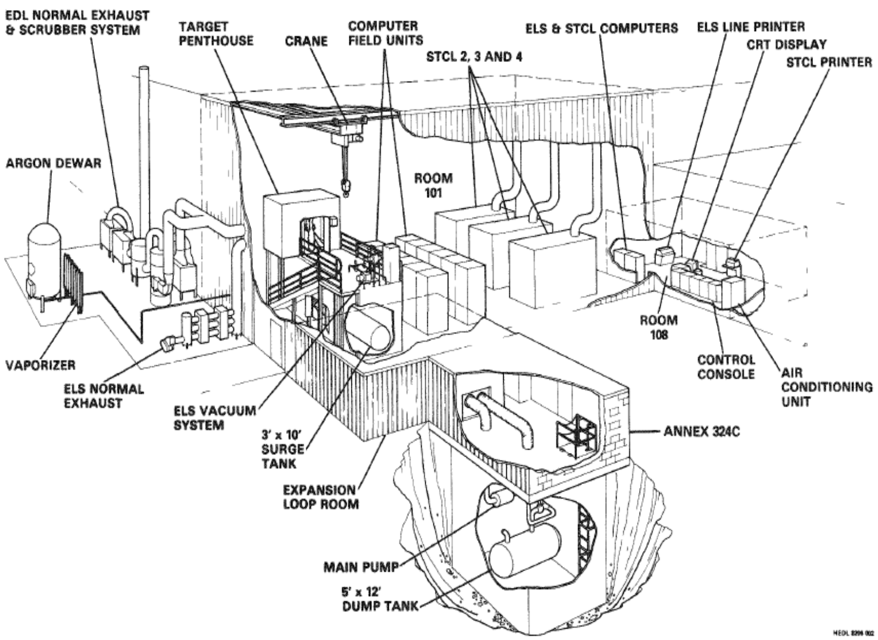


Figure A8 FMIT Lithium Loop Test Facility

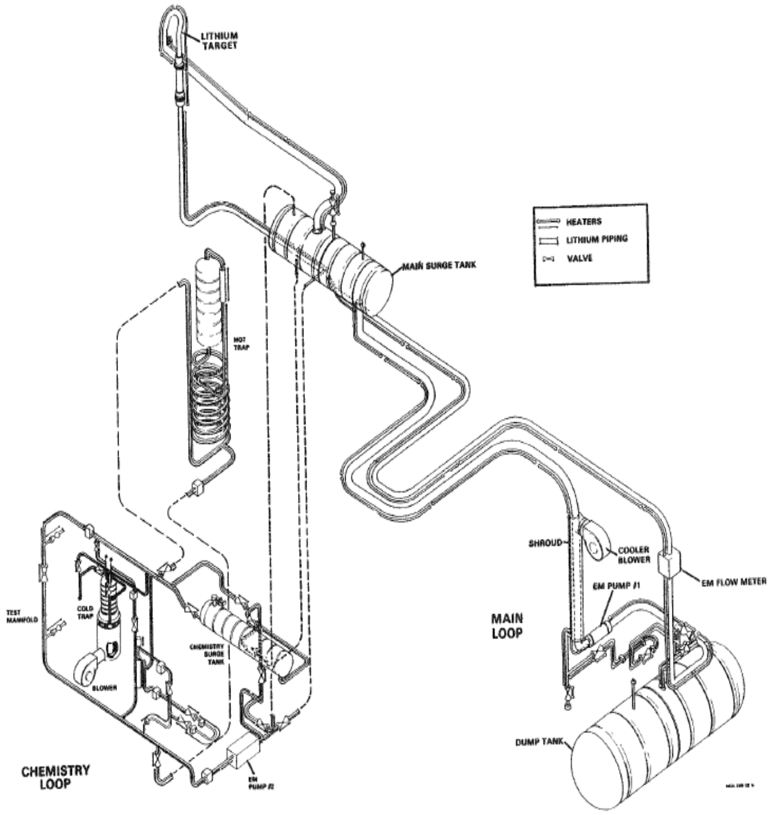


Figure A9 FMIT Lithium Loop Test Facility

PNNL Description

Pacific Northwest National Laboratory has been operated by Battelle since 1965. DOE Office of Science is the Laboratory "Steward". PNNL has unique science and technology strengths and capabilities evidenced by extensive mission-driven collaborations with government, industry and academia. The vision of PNNL is to be recognized worldwide and valued nationally and regionally for leadership in science and for rapidly translating discoveries into solutions for challenges in energy, national security, and the environment.

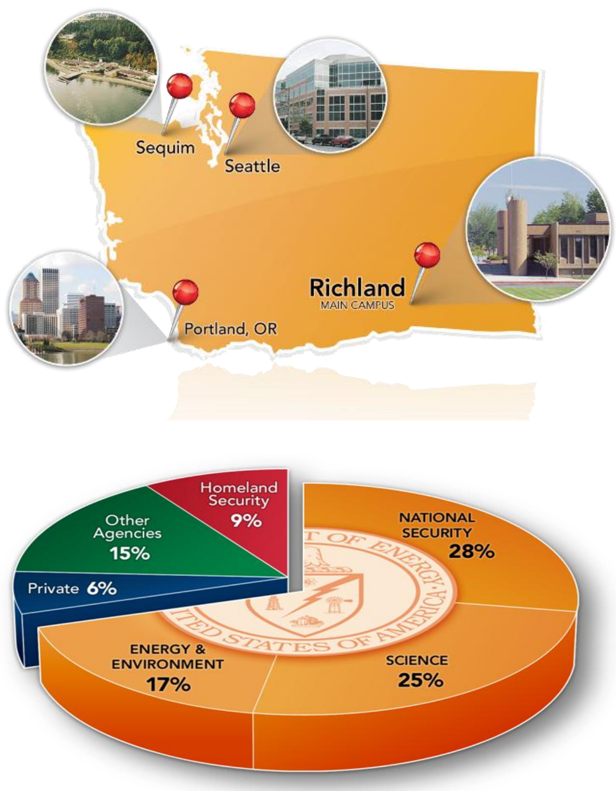


Figure A10 PNNL at a Glance: FY2010

- $1.1B R&D budget
- Nearly 5000 staff, including 3,000 technical staff
- 2000 users & visiting scientist
- 80 R&D 100 awards
- National security: 50% of business
- 930 peer-reviewed publications
- 46 patents issued

- Among top 1% of research institutions in publications and citations in:
    - Chemistry
    - Geosciences
    - Physics
    - Engineering
    - Biology & Biochemistry
    - Environment/Ecology
    - Materials science
    - Clinical medicine
    - Microbiology

PNNL Facilities and experienced staff

- RPL – Radiochemical Processing Laboratory (Hazard Category II nuclear facility)
- MASF – FFTF Maintenance and Storage Facility (currently used for site waste cleanup testing and development
- EMSL – Environmental Molecular Science Laboratory
- APEL – Applied Process Engineering Laboratory
- PSL – Physical Sciences Facility

Nuclear & Particle Physics Research at PNNL Overarching Theme is <u>Weak Interactions.</u> PNNL staff is engaged in five broad areas:

- Neutrino physics
    - Majorana, Project 8
- Dark Matter (CoGeNt)
- Flavor physics (Belle/Belle II)
- Low Energy Nuclear Astrophysics
    - HPGe Array @ FRIB
- Neutron Induced Fission
        - Track alpha and fission products with TPC

Related R&D efforts include:

- Improved photocathode for electron LINAC
- Ion processing of Cu to mitigate electron cloud
- Belle/Belle II computing center
- Nuclear LQCD calculations
- Generic Detector R&D

Nuclear Energy Related Capabilities at PNNL

- Engineering Development heritage
- Facility design experience
- Irradiation testing experience – past FFTF, current Tritium Target Program
- Materials Testing capabilities
  - Hazardous
  - Radioactive
  - Liquid metal
- Path for waste disposal
- Environmental Assessments
- Licensing support
- International collaborations
- PNNL supports both DOE-Nuclear Energy programs and DOE-Office of Science programs

PNNL Tritium Target Testing Experience

- PNNL Tritium Technology Program supports the design, development, demonstration, testing, analysis, and post irradiation characterization of Tritium Producing Burnable Absorber Rods (TPBAR) for NNSA
- Current PNNL program for design, irradiation, postirradiation examination of tests in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) to support production
- Identification of testing needs and incorporating results into production targets
- Testing program follows same path as fuel development
- Basic tests (TMED)
  - Ex-reactor testing to evaluate fundamental material properties
- Separate-effects tests (TMIST-1, TMIST-2, TMIST-3)
  - TMIST (TPBAR Materials Irradiation Separate Effects Test) series of tritium permeation test assemblies
  - In-reactor experiments evaluating effects of individual parameters
  - Allows development of performance models
- Multiple-effects tests (some aspects of TMIST-3)
  - In-reactor experiments evaluating interactions of multiple parameters
  - Allows extension of model predictions to more prototypic conditions
- Integral tests (e.g. TPBAR rodlet in ATR capsule or loop)
  - Verifies understanding of mechanisms and interactions
  - Identifies any remaining unknown phenomena
- Full-size verification (LUA or Surveillance Rod)
  - Fully prototypic verification of scaling from integral test

Irradiation Testing at PNNL in Support of NNSA Defense Programs

Materials Challenges for Defense Programs. The Tritium Technology Program at PNNL supports NNSA Defense Programs in the design, development, demonstration, testing, analysis, and post-irradiation characterization of tritium-producing burnable absorber rods (TPBARs). The TPBARs are irradiated in the Tennessee Valley Authority (TVA) Watts Bar Nuclear commercial power plant to produce tritium for the nation's nuclear weapons stockpile. Over 1300 TPBARs have been irradiated to date, and the quantity irradiated in each Watts Bar operating cycle is increasing to meet stockpile requirements. During irradiation in Watts Bar, the TPBARs release 3.5 ± 0.7 Curies of tritium per TPBAR per year. While this quantity represents only about 0.04% of the tritium produced in each TPBAR, it is considerably higher than the 0.5 Ci/TPBAR/yr predicted by current performance models.

To better understand the discrepancy between predicted and observed tritium permeation, a research program was started in 2006 to provide a scientific basis for improving the performance models. With appropriately designed tests, experimental data can be generated to improve the fundamental understanding behind the mechanisms operating in the TPBAR and hence the accuracy of key predictive models. A fully mature, best-estimate modeling capability will provide a risk mitigation strategy and confidence in design margins, performance predictions, the cost/benefit analyses of future design changes, and the performance impact of those changes.

PNNL Materials Research for Defense Programs. A series of in-reactor and ex-reactor experiments were developed and executed by PNNL through collaboration with Idaho National Laboratory (INL). The irradiation tests comprise the TPBAR Materials Irradiation Separate-Effects Test (TMIST) series, while the related ex-reactor tests comprise the TPBAR Materials Ex-Reactor Testing and Development (TMED) series. The experiments focus on separate-effects performance of individual materials used in the TPBAR in an effort to elucidate in-reactor behavior of each TPBAR component. In many cases, it has been observed that material properties and performance are significantly different in the reactor environment than when evaluated under identical conditions out of reactor. Thus, a prime focus of the effort has been comparison of in-reactor and ex-reactor behavior and development of appropriate in-reactor performance models to predict TPBAR tritium releases.

The TMIST irradiation experiments are conducted at the Advanced Test Reactor at INL. The test parameters and in-core experiment hardware are designed, fabricated, and assembled by PNNL in the Tritium Target Fabrication Facility in the Salk Building and other facilities on the PNNL campus. Specialized capabilities that are utilized in the fabrication and assembly of irradiation experiments include electron beam and laser welding, precision machining via CNC and EDM, and inspections using a three-dimensional coordinate measuring machine. The out-of-core experiment hardware is designed, fabricated, assembled, and operated by INL. Post-irradiation examination of the TMIST experiments is conducted at both PNNL and INL.

TMIST-1 and TMED-1 – The TMIST-1 and TMED-1 experiments, completed in 2009, investigated the oxidation and hydrogen uptake behavior of various Zr-base alloys in in-reactor and ex-reactor settings, respectively. The materials of interest include current and candidate materials for TPBAR liners, which are designed to reduce T_2O or HTO released by the lithium aluminate pellets in the TPBAR so the elemental tritium can be absorbed by the Ni-plated, Zr-base alloy getters. It is important for liners to possess high oxidation rates and it is beneficial for them to pick up some of the reduced tritium, but liners must also retain their structural integrity throughout life to prevent pellet relocation. The TMIST-1 and TMED-1 experiments ran for 138 days at identical temperature and D_2O partial pressure conditions. The experiments demonstrated important differences between in-reactor and ex-reactor oxidation and hydrogen uptake behavior for the various alloys, and they provided more accurate data on which to base liner performance models as a function of both temperature and T_2O partial pressure.

TMIST-2 – The TMIST-2 experiment, completed in 2010, investigated the in-reactor tritium permeation behavior of TPBAR cladding materials as a function of temperature and T_2 partial pressure. The cladding is an austenitic stainless steel with an aluminide tritium barrier coating applied to the inner surface. The TMIST-2 data demonstrated that there is a significant irradiation enhancement of tritium diffusion through bare (uncoated) stainless steel. As a result, the permeation reduction factor of barrier-coated stainless steel appears to be lower than current performance model assumptions. The models will be updated to include these new data, which will reduce the discrepancy between predicted and observed TPBAR tritium permeation. The TMIST-2 experiment also included an evaluation of the possible permeation-enhancing effect of ^{3}He transmutation and implantation directly into the cladding. This is a good example of a possible permeation mechanism that could not be evaluated in any way other than a dedicated irradiation experiment.

TMIST-3 and TMED-3 - The TMIST-3 and TMED-3 experiments are focused on evaluating the irradiation performance of lithium aluminate pellets that are used to generate tritium in a TPBAR through neutron interactions with Li-6. Because the pellets are the source of tritium in TPBARs, it is important to understand the time, burnup, burnup rate, and temperature dependence of tritium release from the pellets. In addition, it is important to understand the speciation of the tritium release (i.e. HT versus HTO) and how the speciation might change with time and burnup. The TMIST-3 irradiation experiment will also evaluate the impact of various microstructural features on pellet tritium release including grain size, porosity, and pore morphology. Finally, TMIST-3 will evaluate the performance of alternate pellet materials such as lithium aluminate/zirconium cermets that combine the functions of pellet, liner, and tritium getter that are presently three separate components in a TPBAR. The TMED-3 experiment is being executed to evaluate different pellet configurations, material characteristics, and advanced materials that could provide TPBAR designers with options for reducing permeation, decreasing rod internal pressure, or improving structural integrity of other components by changing their volume. Ultimately, the goal of TMED-3 is to produce small quantities of specialized pellets for the TMIST-3 pellet performance irradiation experiment. The TMIST-3 irradiation experiment is scheduled for insertion in ATR in 2012.

Post-Irradiation Examination – Another important aspect of the research into TPBAR performance characteristics is the use of post-irradiation examination (PIE) on TPBARs previously irradiated at Watts Bar. The advantage of PIE on these rods is that the materials, configuration, and irradiation conditions are fully prototypic. Whereas irradiation experiments such as the TMIST series evaluate the separate effects of parameters such as time, temperature, burnup, and material type on individual TPBAR components, PIE on irradiated TPBARs allows an integral evaluation of end-of-life conditions with all components interacting in a prototypic fashion. The data obtained from PIE provide good benchmarks for TPBAR performance models, as well as a way to evaluate model predictions on observable TPBAR characteristics. Post-irradiation examination has been conducted on TPBARs irradiated in three different Watts Bar operating cycles, representing three distinct TPBAR designs. The PIE campaigns are conducted in the hot cell facilities and laboratories of the Radiochemical Processing Laboratory, and include characterization techniques such as gamma spectroscopy, rod puncture and gas analysis, protium and tritium assays in the various TPBAR components as a function of axial position, retained tritium and helium assays in the pellets, Fourier transform infrared spectroscopy to determine oxide layer thicknesses on the Zr-base components, He-3 and He-4 assays in the stainless steel cladding, and optical and scanning electron microscopy and electron dispersive x-ray spectroscopy of irradiated TPBAR components.

Figure A11 Fixturing the TMIST-1 test train in the electron beam welder.

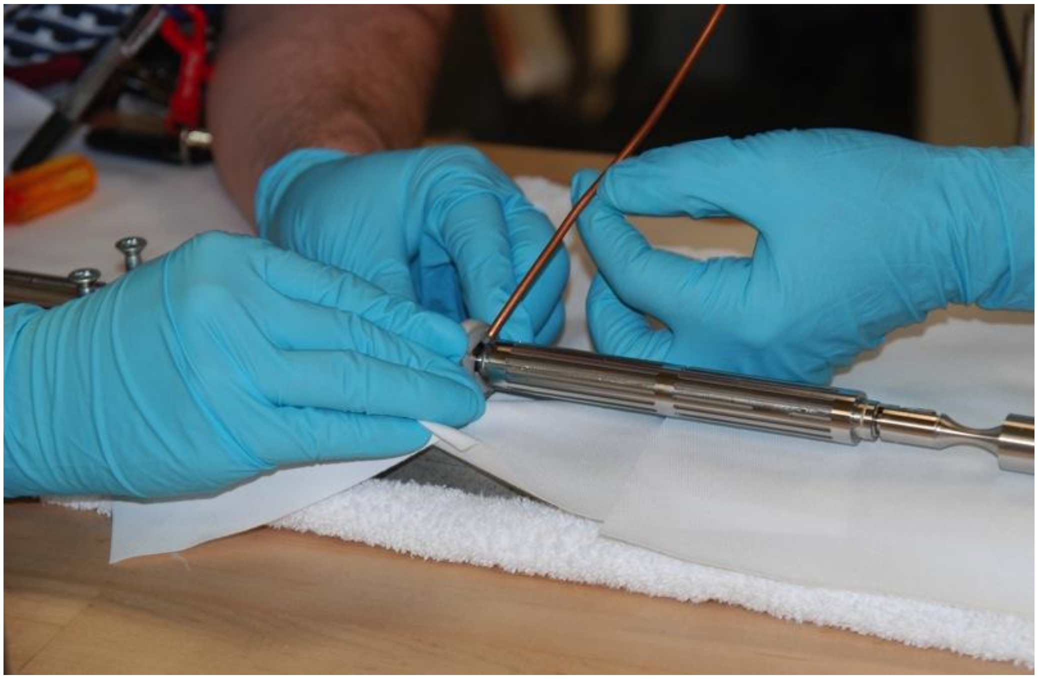


Figure A12 Performing He leak check on a TMIST-1 capsule after electron beam welding.

Figure A13 Receiving the GE-2000 cask containing the irradiated TMIST-2 test train at RPL.

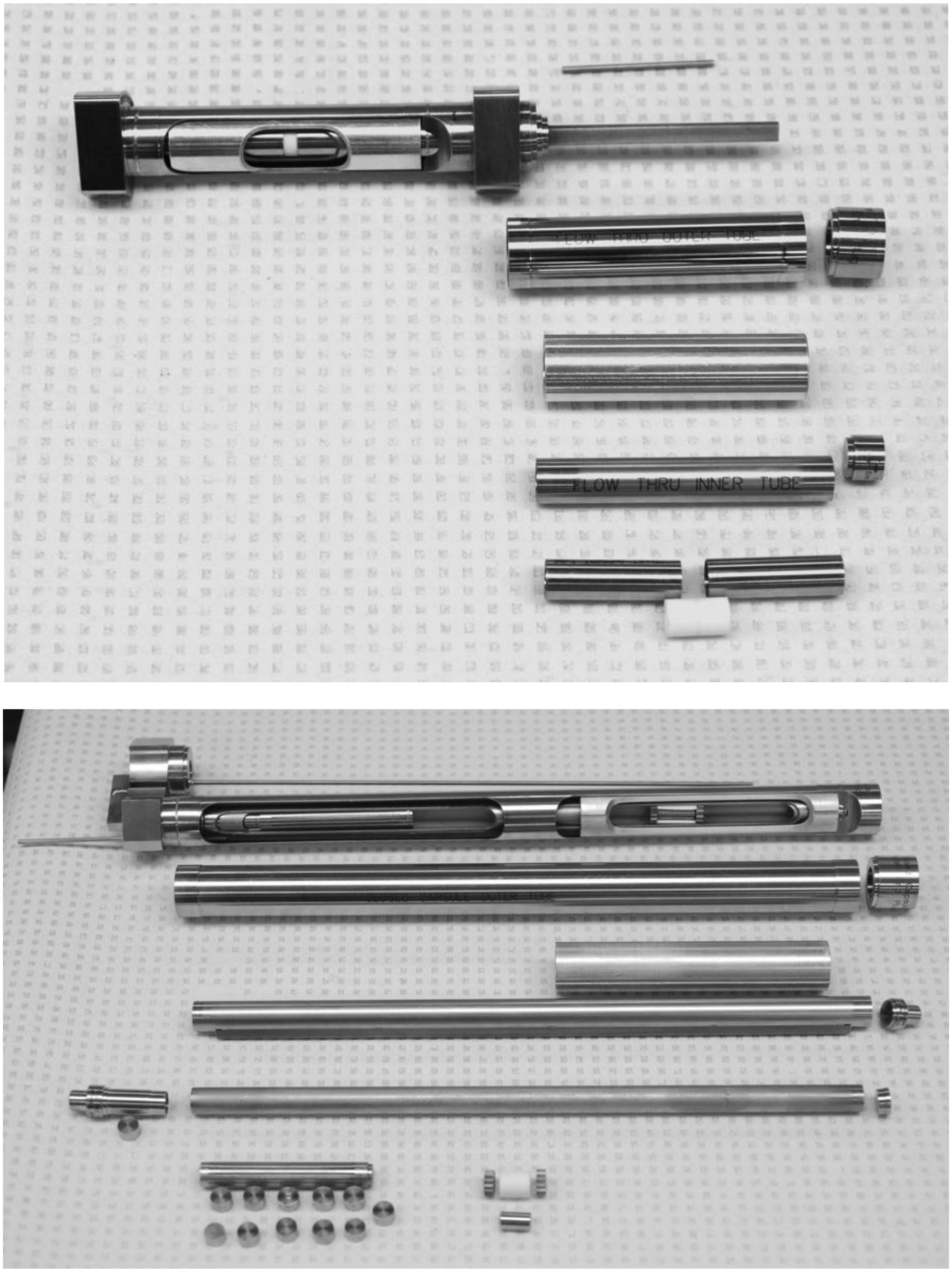


Figure A14 Stock Prototype cutaway capsules showing the internal components and arrangement of flow-through (top) and closed (bottom) capsules designed for the TMIST-3 irradiation experiment to evaluate different aspects of lithium aluminate pellet performance.

The Project X Energy Station could be used to explore fundamental science issues that directly support the tritium program. There are a number of possible experiments at the proposed Energy Station that could be performed that would be very useful. For example, experiments could be set up to explore permeation and materials performance. The unique capabilities such as access for instrumentation in the Energy Station modules may even allow some testing that could not be conducted in a test reactor. The Energy Station might also be configured to support NDE examinations (PIE) of tritium targets using a neutron beam as a tool.